STORAGE BATTERY ENGINEERING

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STORAGE BATTERY ENGINEERING

A PRACTICAL TREATISE FOR ENGINEERS

BY

LAMAR LYNDON

THIRD EDITION, REWRITTEN AND ENLARGED

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PREFACE TO THE THIRD EDITION.

SINCE this book first appeared nearly a decade has elapsed—a period of time which is commonly reckoned as a generation in the electrical art.

During these years many changes have been incorporated in storage-battery practice, new forms of electrodes and auxiliaries have been devised, and a number of once familiar plates and apparatus have passed into the obscurity of the discarded and superseded.

Equally marked is the improvement in the general understanding of this branch of engineering on the part of engineers and operators of plants, to which diffusion of knowledge of the storage-battery art it is believed the first editions of this work contributed no small part.

For all these reasons a thorough rewriting of this book became necessary.

It will be seen that the present treatise not only considers the practical features of the art as it exists to-day, but considerably more of the theoretical side is included. Examples are the chapters on Electrolytic Dissociation, the Thermodynamical Theory of the Lead Cell, and the fuller discussions in each of the other chapters in the first half of the book. It is believed that the practical instruction which it is the object of this work to furnish will not suffer from this additional material, as nearly all the theoretical portion may be omitted in the reading, without the text becoming broken or disconnected.

Although the manufacture of pole-wound boosters has been discontinued, so many machines of this character are in service that it has been considered advisable to retain the discussions of the principal types.

The author here acknowledges the courtesy of the Gould, Westinghouse, National and General Electric companies for data, diagrams and photographs. Also he expresses his obligations to Dr. Louis Duncan, Dr. W. E. Winship, Dr. A. S. Chessin and Mr. Edward Lyndon for assistance and suggestions.

LAMAR LYNDON.

November, 1910.

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PART I

STORAGE BATTERY ENGINEERING

CHAPTER I.

ELECTROLYTIC DISSOCIATION AND THE VOLTAIC COUPLE.

WHEN an electric current passes through any non-metallic liquid which has electrical conductivity, chemical decomposition takes place, and some or all of the chemical constituents of the liquid are either separated into their component parts or new combinations of elements are produced.

This phenomenon is known as *electrolysis* and it can take place only in conducting liquids, which are called *electrolytes*.

Electrolytes may be normal liquids or solids brought to a liquid state by fusion, and maintained in this condition by continued application of heat. Electrolytes which are liquid at ordinary temperatures, and which are used in electric batteries, are made up of mixtures of acids, bases or salts dissolved in water or other solvent. Solutions in water of common salt, sulphuric acid, potassium hydrate, sodium hydrate and the like are examples. Most organic liquids, such as alcohol, ether, aldehydes and hydrocarbons, and chemically pure water, are poor conductors of electricity, and no electrolytic decomposition takes place when they are subjected to ordinary electrical potentials.

Since all conductors used in electrical machinery for the transmission of current, are either of metals or carbon, it is necessary to have two metallic or carbon conductors immersed in the liquid or electrolyte in order to pass the current through it. These two immersed conductors are called *electrodes* or *poles.* The conductor attached to the wire connected with the positive pole of the dynamo or other source of current is called the *anode.* The other conductor attached to the negative pole of the dynamo or current source is called the *cathode.* The current flows from the positive pole of the dynamo to the anode, leaves the anode to

pass into the liquid, travels through the liquid and reaches the cathode, by which means it leaves the liquid and goes to the negative pole of the dynamo. All chemical dissociation or combination manifests itself at these two electrodes, either where the current leaves the anode to enter the liquid, or where it leaves the liquid to pass to the cathode, and nowhere else in the body of the electrolyte.

Ions are the carriers which transport the electricity through the electrolyte. They are supposed to be atoms, or groups of atoms, which are charged either positively or negatively and to move in a continuous procession through the electrolyte, the negatively charged ions or *anions* passing in a direction opposite to that of the current flow, to the anode, and there giving up their negative charges, which are neutralized by the positive charge of the anode, while the *cations* move in the same direction as that of the current flow, towards the cathode, and there give up their positive charges, which are neutralized by the negative charge of the cathode.

The phrase " direction of current " is used here simply to indicate a movement from the anode to the cathode, but, in truth, there is no current flow other than that caused by the continuous transfer of charge bv the ions as described.

An ion, then, is simply an atom or a group of atoms, charged with a certain quantity of electricity, which it transfers from one electrode to the other.

When molecules are dissociated into atoms or groups of atoms bearing an electrical charge or, in other words, when ionized, they have not the same chemical properties that a molecule or group of molecules of the same substance would have, if not in an ionized state.

Ions are formed in four different ways, which are : *

I. A molecule, under certain conditions, breaks down into an equivalent number of anions and cations.

II. An atom takes a charge from an ion, thereby becoming itself an ion, and the original ion, being deprived of its charge, becomes an atom.

III. One substance passes from the condition of an atom to that of a cation, while another substance passes at the same time from the condition of an atom to the corresponding anion.

* Outlines of Electro-Chemistry. H. C. Jones.

IV. An ion receives an additional charge of electricity and converts an atom into an ion having an opposite charge.

As is well understood, the usual products of electrolysis of dilute acid solutions are oxygen and hydrogen. The oxygen appears at the anode, while the hydrogen forms at the cathode, both appearing as free gases, except when the electrodes are of such chemical composition that the oxygen and hydrogen can combine with them to form new substances. The quantities of oxygen and hydrogen formed by the passage of current are always in a strict proportion, viz., eight times as much of oxygen as of hydrogen by weight, or twice as much hydrogen as oxygen by volume, these being the proportions of these two gases in the formation of water.

Whenever chemical dissociation is produced, energy is required, the energy necessary being proportional to the amount of heat set free when the compound was formed by the combination of its constituent molecules. Conversely, when chemicals in an electrolyte combine to form a new substance, the heat energy of formation may manifest itself as electrical energy instead of heat, which fact makes possible the electric battery.

All substances which require energy for their decomposition and which give out energy on formation are called *endothermic* which is the property of most compounds. A few, however, which are called *exothermic* give out energy when decomposed and require energy to effect their formation.

Faraday formulated the following laws, which have been amply confirmed since he first announced them:

I. The amount of a substance liberated at an electrode is proportional to the total quantity of electricity passed through the cell.

II. The amount of a substance liberated by a given quantity of electricity is proportional to the electro-chemical equivalent of the corresponding ion.

III. The amount of a substance liberated is *equal* to the electro-chemical equivalent of the corresponding ion $\times$ total quantity of electricity. Thus $W = Z \times Q$; that is, wt. in grams = electro-chem. equiv. $\times$ no. of coulombs.

Hence, for a steady passage of current of c amperes for t seconds,

$$Q = ct, \text{ and } W = Zct.$$

The electro-chemical equivalent of a substance is the ratio of the quantity, by weight, of the substance which is decomposed by one coulomb of electricity, to the quantity of hydrogen liberated by the passage of one coulomb. Numerically, it is equal to the atomic weight of the substance divided by its valency. The atomic weight and valency of hydrogen being both equal to 1, its electro-chemical equivalent is unity, and for this reason it is taken as the unit.

That for oxygen $= 16 \div 2 = 8$; for lead $= 206 \div 2 = 103$.

The table herewith gives a list of the elements, the atomic weights, valencies, grams liberated per coulomb, grams liberated per ampere hour, and coulombs required per gram liberated, for each.

It will be noted that a few substances have more than one valency, depending on the form in which they are combined with other elements. They therefore have more than one electro-chemical equivalent, which is to say that in a certain combination more of the element is dissociated by a given quantity of electricity than if in some other combination where its valency is greater.

The laws of Faraday relate only to the *quantity* of electricity necessary to liberate a given weight of a substance. The *energy* required to produce a disruption of any substance is the product of the electro-motive force multiplied by the quantity of electricity or energy $= EQ$, in which $E =$ electro-motive force, $Q =$ coulombs, the product being expressed as *volt-coulombs* or *joules*. Bertholet has shown this energy to be strictly proportional to the quantity of heat liberated by the chemical formation of a molecule of the substance, and therefore, the electro-motive force produced by an electric battery is proportional to the heat released by the chemical combination.

This heat, absorbed by any chemical reaction, is known as the "heat of formation." Later, in Chapter IV, its use in connection with electro-motive force computations will be shown.

Volta discovered in 1790 that if electrodes of two chemically dissimilar conducting substances are immersed in an electrolyte, which can attack one or both the electrodes, an electro-motive force is produced which gives rise to a current flow when the external circuit between the two electrodes is closed. While the circuit remains open, little or no chemical decomposition takes place, and

TABLE I.

Elements.	Symbols and Valencies.	Atomic Masses.*	Chemical Equivalents.	Electro-Chemical Equivalents. Grams per Coulomb.	Grams per Ampere-Hour.	Ampere-Hours per Gram.	Pounds per Ampere-Hour.	Ampere-Hours per Pound.
Aluminium †	Al III	26.9	8.965	.0000936	0.3370	2.9674	.000743	1346.0
Antimony	Sb III	119.5	39.83	.0004157	1.4965	0.6682	.003299	303.1
Bromine	Br I	79.34	79.34	.0008281	2.9812	0.3354	.006572	152.1
Calcium	Ca II	39.8	19.90	.0002077	0.7477	1.3374	.001648	606.6
Carbon	C IV	11.9	2.975	.0000310	0.1116	8.9606	.000246	4064.5
Chlorine	Cl I	35.18	35.18	.0003672	1.3219	0.7565	.002914	343.1
Copper (cupric)	Cu II	63.1	31.55	.0003293	1.1855	0.8435	.002614	382.6
Copper (cuprous)	Cu I	63.1	63.10	.0006586	2.3710	0.4218	.005228	191.3
Gold	Au III	195.7	65.21	.0006809	2.4512	0.4080	.005404	185.1
Hydrogen	H I	1.000	1.000	.00001044	0.0376	26.5957	.000083	12063.6
Iodine	I I	125.89	125.89	.0013140	4.7304	0.2114	.010429	95.9
Iron (ferric) †	Fe III	55.6	18.53	.0001934	0.6962	1.4364	.001535	651.5
Iron (ferrous)	Fe II	55.6	27.80	.0002902	1.0447	0.9576	.002302	434.4
Lead	Pb II	205.36	102.68	.0010718	3.8585	0.2592	.008506	117.6
Magnesium	Mg II	24.1	12.05	.0001258	0.4529	2.2080	.000998	1001.5
Manganese	Mn II	54.6	27.30	.0002850	1.0260	0.9747	.002262	442.1
Mercury (mercuric)	Hg II	198.5	99.25	.0010360	3.7296	0.2681	.008222	121.6
Mercury (mercurous)	Hg I	198.5	198.50	.0020719	7.4588	0.1340	.016444	60.8
Nickel	Ni II	58.25	29.125	.0003040	1.0944	0.9137	.002413	414.4
Nitrogen	N III	13.93	4.64	.0000484	0.1742	5.7405	.000384	2603.8
Oxygen	O II	15.88	7.94	.0000829	0.2984	3.3512	.000658	1520.1
Platinum (platinic)	Pt IV	193.4	48.35	.0005047	1.8169	0.5504	.004006	249.7
Platinum (platinous)	Pt II	193.4	96.70	.0010094	3.6338	0.2752	.008012	124.8
Potassium	K I	38.82	38.82	.0004052	1.4587	0.6855	.003216	310.9
Silver	Ag I	107.11	107.11	.0011180	4.0248	0.2485	.008873	112.7
Sodium	Na I	22.88	22.88	.0002388	0.8597	1.1632	.001895	527.6
Tin (stannic)	Sn IV	118.1	29.525	.0003082	1.1095	0.9013	.002446	408.8
Tin (stannous)	Sn II	118.1	59.05	.0006164	2.2190	0.4506	.004892	204.4
Zinc	Zn II	64.9	32.45	.0003387	1.2193	0.8201	.002688	372.0

* From the report of the Committee on Atomic Weights to the American Chemical Society, February, 1900.

† Effective Valency, or number of Hydrogen atoms it will replace.

the electrode subject to attack by the electrolyte, is not acted on at all, or to a slight degree only. As soon, however, as the external circuit is closed, a flow of electricity takes place, the chemical action becomes violent, and the attackable electrode is either gradually eaten away, being dissolved in the electrolyte, or it combines with the electrolyte to form another substance.

The amount of the electrode destroyed or converted was found to be proportional to the quantity of electricity which was taken from the cell, and conversely, the quantity of electricity which a cell is capable of giving out is proportional to the amount of chemical substances in the electrodes with which the electrolyte may combine.

Any two chemically dissimilar electrodes which give rise to an electro-motive force when immersed in an electrolyte are called a *voltaic couple*. Two classes of such couples are in commercial use; one in which the exhaustion of the materials, either of the electrodes or electrolyte, requires the removal of the substances formed by their combination and the substitution of fresh materials in order to rejuvenate the cell.

The other class is that in which the electrodes are not dissolved but, when the battery gives out current, some of the chemicals in the electrolyte combine with the electrodes, augmenting their bulk and weight, and when the chemicals available, either of the electrodes or the electrolyte, have so far combined, through the act of producing current, as to finally reach a condition of exhaustion, the battery may be rejuvenated and brought back to its condition of usefulness by the reverse action of current.

Any voltaic couple which is reversible, *i.e.*, capable of regeneration after exhaustion by passing an electric current through it in a direction opposite to that of flow on discharge, is a storage battery or accumulator.

There are many couples which fulfill this condition and can be used as storage batteries, but with the exception of lead peroxide against lead, and lead peroxide against zinc, none, so far, has proven commercially available for engineering purposes. Edison and Jungner have produced iron-nickel cells which promise to be of value in electric motor-car propulsion, but because of their low efficiency, as elsewhere explained in this work, they can never compete with the lead-lead battery for power station service.

The lead-lead cell being in general use — practically to the exclusion of all other types — it, only, will be considered in detail here. The engineering applications and methods of installation will be of the same character for any type of battery used, the only differences being in the electro-motive forces of the individual cells, and the corresponding number of cells required for any given equipment.

CHAPTER II.

DESCRIPTION AND CHARACTERISTICS OF THE LEAD CELL.

THE lead-lead battery consists of two electrodes or sets of electrodes, the positive and negative, immersed in the electrolyte. The two electrodes are sponge lead, (Pb), for the negative, and peroxide of lead, (PbO_2), for the positive, these forming the active couple, the electrolyte being dilute sulphuric acid. The two sets of electrodes are called an element. The positive and negative electrodes can readily be distinguished by their colors when they are in good condition. The peroxide plate is of a velvety brown chocolate color and the lead sponge plate is a light gray. They are also distinguishable by their hardness, the positive being usually hard like soapstone, while the negative is soft and can be easily cut into with the thumb nail.

Sponge lead is not ordinary metallic lead, but some allotropic form of this metal. Its conversion into the ordinary form of lead is accompanied with the production of heat.

Darrieus has shown that the electro-motive force between soft metallic lead and lead peroxide immersed in dilute sulphuric acid of about 1.225 sp. gr. is 1.46 volts, while under the same conditions of temperature, acid concentration and disposition of plates the electro-motive force between electrolytically formed lead-sponge and lead-peroxide is 1.94 volts.

When the cell gives out current, the elements gradually change in composition, becoming mixtures or compounds of lead and lead sulphate at the negative electrode, and lead peroxide and lead sulphate at the positive electrode, the chemical change caused by the giving out of electrical energy being a gradual formation of lead sulphate.

The chemicals, lead and lead peroxide, are called the "active materials."

The electrodes are usually made in the form of flat, thin plates, there being several positives and negatives in each cell. The posi-

tives are all connected together in one group to a common terminal and the negatives are connected in another similar group, the two sets of plates being interleaved with each other, so that each positive plate has adjacent to and facing it on either side, a negative plate. The plates are usually set vertically in the containing jar or cell, except in certain special cases.

The adjacent plates being of opposite polarity, they must be kept well separated and insulated from each other, as electrical contact between the two groups at any point will short-circuit the entire cell. For this reason separators are placed between the plates to prevent any contact between them. These separators must not prevent the circulation of electrolyte from plate to plate, nor its contact with the plates. Glass rods, perforated hard rubber and porous wood are principally used as separators.

When the electrodes are in a condition to give out current, the battery is said to be charged. The process of giving out current is called discharge, and when an amount of electrical energy has been taken from the cell which brings its electro-motive force down to a predetermined safe limit, — 1.7 to 1.8 volts, — it is said to be discharged. The process of sending current into the cell from an outside source in a direction opposite to the flow on discharge, and thereby reducing the exhausted chemicals back to their original useful condition, is called charge. Obviously, the term "charged" does not mean that any electricity is stored in the cell or resides in the electrodes. It means that the chemical condition of the elements is such that they form an active voltaic couple or cell which, in its general behavior, differs in no wise from any ordinary, primary element.

A charged cell, then, is one in which the active material of the positive plates is lead peroxide, and that of the negatives is sponge lead, while a discharged cell is one in which a portion of the active material on each plate has been converted into lead sulphate.

The electric current when flowing through the cell in the direction of charge has the function of a chemical reducing or oxydizing agent only, and when passing in the direction of discharge the current given out is produced by the energy of chemical combination.

It is customary to call the peroxide plate the positive, because the current discharging from the cell flows out from the peroxide plate, and therefore it stands in the same relationship to the exter-

nal circuit as does the positive pole of a dynamo. Considered voltaically, however, the peroxide plate is the negative and the sponge lead plate is the positive, because in the interior of the cell the current flows from the lead sponge to the peroxide. In the voltaic series, sponge lead is a highly electro-positive substance, while lead peroxide is the most electro-negative of any known substance. This means that when the two are immersed in an electrolyte and connected by an outside circuit, current flows inside the cell from the voltaic positive to the negative. Obviously, viewed from the voltaic standpoint, current flows out of the cell from the negative electrode, but according to the rule that the positive pole or terminal is that from which current leaves a source of electrical energy to pass to the external circuit, the lead peroxide electrode is the positive. This being the engineering usage, it will be adhered to in this work.

As stated before, the discharge of a cell is attended by the formation of lead sulphate. Pure lead sulphate, ($PbSO_4$), when isolated, is white in color, has a high resistance, being in fact an insulator, and its volume is greater than that of the lead or lead peroxide of which it is formed. Therefore a cell should never be discharged below some fixed limit, because the excessive quantity of sulphate formed will injure the plates both electrically and mechanically, tending to crack and loosen the active material. Cells which have been too far discharged, and thereby had too much sulphate produced, are said to be sulphated. This condition is indicated by the deposit of white sulphate on the surfaces of the plates.

The unit of cell capacity is the ampere-hour, which is the equivalent of one ampere flowing for one hour. The ampere-hour capacity of any cell on discharge is the product of the rate of flow, in amperes, multiplied by the number of hours the current rate is maintained. If the discharge is variable, the capacity is the summation of the products of each of the various rates multiplied by its duration in hours.

The capacity varies with the rate of discharge and the temperature, decreasing with the rate and increasing with the temperature. Therefore it is necessary to adopt a standard temperature and rate of discharge in order to definitely specify battery capacity. The standards are taken as the 8 hour rate for discharge at a temperature of 70 degrees F. or 15.5 degrees C.

The 8 hour rate is the current flow which a battery will give for 8 hours continuously without falling below the allowable minimum voltage. Thus an 80 ampere-hour battery means one which will discharge 10 amperes continuously for 8 hours. Other things being equal, the rate at which a battery may be discharged depends on the area of active material surface in contact with the electrolyte. In computing the active area the positive plates are taken as the basis, for the reason that the number of negative plates in a cell is greater by one than the number of positives, except in the special case of a simple couple or two plate cell. The active area of each positive plate is its breadth multiplied by its (submerged) length and this product is doubled because the two surfaces of the plate are active. The active area of any cell on this basis is, of course, equal to the active area of each positive plate multiplied by the number of positive plates in the cell.

The voltage or electro-motive force of a cell is dependent only on the character of the materials in it and the temperature, and is independent of the size of the cell. The voltage of the lead-lead cell is approximately 2 volts. When the usual working voltages necessary for electrical service and distribution are required, a sufficient number of cells are put in series to give the desired pressure. Thus on a 100-volt circuit approximately 50 cells are required, while on a 500-volt circuit approximately 250 cells must be connected in series, each cell having the desired capacity for the current output taken by the system.

With the formation of lead sulphate at the two elements on discharge, the voltage of the cell gradually decreases until the minimum allowable value is reached, — usually 1.8 volts, — when the cell is considered to be fully discharged. If after complete discharge the cell be allowed to stand idle for a short time, say from one to two hours, it will be found to have some additional capacity and can again give out current. This is called the residual charge, and is due to the fact that the diffusion of electrolyte into and out from the minute pores in the active material is retarded by a surface layer of lead sulphate. When discharge takes place, the sulphuric acid of the electrolyte yields up a portion of its constituents, which go to form the lead sulphate. At first, the chemical action takes place most rapidly at the surface of the plates and the resulting formation of sulphate tends to

close up the pores in the active material by reason of the resulting increase in volume. The continuation of discharge requires the abstraction of a portion of the chemical constituents from the electrolyte imprisoned in the pores of the plates, and the amount of electrolyte thus available is very small. When this is exhausted the cell has been fully discharged. On standing, however, the electrolyte outside the plates slowly diffuses into the pores and provides an additional amount to make the cell again active, which is the source of the residual charge.

Like every other electrical device the storage battery has a certain efficiency which is the ratio of the electrical energy given out by the cell to the energy required to recharge it. This efficiency varies with so many factors that all the conditions of working must be given before any value assigned it can have any meaning. The standard conditions are 8 hour rates of charge and discharge, temperature 70 degrees F. maintained constant throughout the cycle of discharge and recharge. Many other details enter into this question, as are fully set forth in Chapters XII and XIX.

Every cell has an internal resistance, which also is a variable. This causes a drop in the cell potential when discharging and an increase when charging current is being sent into it. The actual drop or actual increase, however, is much greater than that due to the current flow multiplied by the resistance. The principal factor which causes these changes in potential at the battery terminals is polarization.

Polarization is a phenomenon which occurs on the passage of current between two electrodes immersed in an electrolyte, and its effect is always to oppose the flow of current and to reduce it.

It is customary to consider all effects resulting from electrolytic decomposition which oppose the current producing them, as polarization. There are, however, two different causes which tend to obstruct current flow, namely, increase in ohmic resistance and in counter electro-motive force. The author prefers to consider the change in ohmic resistance as such only, and confine the meaning of the term " polarization " to the counter electro-motive force effects.

The passage of current through the electrolyte decomposes some or all the compounds of which it is formed, and on breaking up, the elements or other compounds which are released may be dissolved in the electrolyte; may pass off in the form of gas; may surround

the electrodes as a film; may be absorbed or occluded in the pores of the electrode or may enter into chemical combination with the material of the electrodes.

The formation of a film, whether gaseous or of some salt of the material of which the electrodes are made, would increase the resistance by diminishing the area of the current path. The change in the concentration or the chemical composition of the electrolyte or electrodes, or the action of the gases occluded by the electrodes, will set up a counter electro-motive force and the joint action of these two effects is to oppose the flow of current.

The most important of all the polarizing agents liberated is hydrogen. This being electro-positive, it travels to the cathode which is the negative on charge and the positive on discharge, and sets up an electro-motive force in opposition to that producing current flow.

Nernst has shown that for electrolytic decomposition, the electro-motive force between the electrodes is not simply that necessary to decompose water, but to the potential which will decompose water must be added an amount which varies with the character of the electrodes. This additive factor depends for its value on the ability of the electrodes to occlude hydrogen, varying inversely with the occlusive capacity. The greater, therefore, the quantity of hydrogen which can be occluded by a given volume of the electrodes, the less is the additive factor, and the less the total voltage required for electrolytic decomposition. Since lead has the property of occluding but little hydrogen, its additive factor is high, hence the electro-motive force between lead peroxide and sponge lead electrodes is 2 volts and above, although the voltage of decomposition of water is only 1.35 volts. This simply is an example of polarization due to hydrogen. If hydrogen can be occluded it produces little or no counter electro-motive force, while no occlusion means that the hydrogen is free to set up a counter pressure.

The voltage of a storage battery rises gradually as charge proceeds, until a maximum is reached. When discharge takes place, the voltage sinks gradually until the minimum allowable value is attained. These voltage changes are usually represented by diagrams called voltage curves, which are simply curves drawn on rectangular co-ordinates, the abscissæ representing the time in minutes or hours and the ordinates the voltage at the terminals

of the cell. By reference to these curves, the voltage at any period during the time of charge or discharge may be determined, and by comparison of the charge and discharge curves plotted to the same scale, the characteristics of a cell for a single cycle may be computed.

It is evident, from what has preceded, that the more porous the active material, and the better the circulation of the electrolyte, the less will be the fall in the voltage curve, as discharge proceeds. Figure 1 shows charge and discharge curves of a certain cell. It will be seen that the curve of charge consists of three parts, one during which the voltage rises suddenly at the beginning of charge; the second part during which the voltage stays reasonably constant at between 2.2 and 2.3 volts, and the third part occurring towards the end of charge, being a rapid continuous rise from about 2.3 to 2.6.

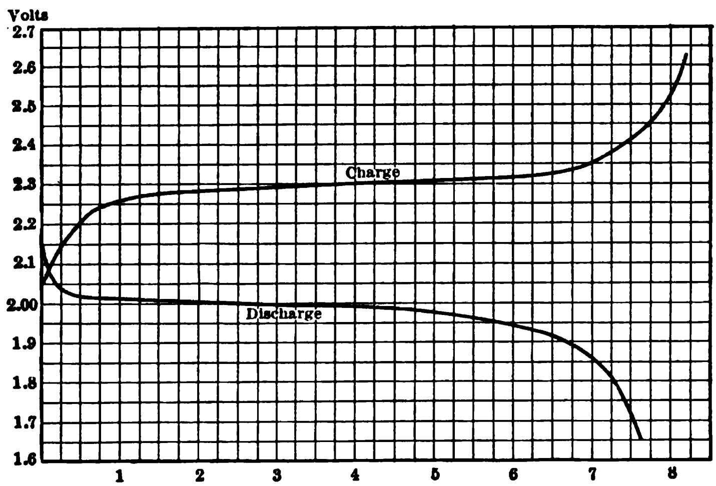


Fig. 1. Curves of Charge and Discharge.

It is probable that intermediate chemical changes begin to take place at the point where the curve begins to rise rapidly at the end of charge and also that gas is produced and the effects of polarization become more marked.

The discharge curve also shows a like form, except in a reverse direction: the voltage falls quickly to about 2 volts, and then continues at very nearly a constant value until a certain point in the curve is reached toward the end of discharge, when it begins to fall off rapidly. This sudden fall in voltage is due to a number of

causes, the most important of which is the formation of sulphate on the surface of the plate, preventing access of electrolyte to the inner pores of the active material, and greatly increasing the ohmic resistance of the cell. The electrolyte, which is enclosed in these pores, rapidly turns to water by reason of abstraction of SO_3 from H_2SO_4.

There are two generic types of storage battery plates; one, known as the Planté type, is made by preparing lead plates so that a large area is exposed and then chemically or electro-chemically oxidizing the surface into lead peroxide, which forms the positive plates. To form negatives, the peroxide plates are connected as cathodes with lead sheets as anodes, in a bath of dilute sulphuric acid, and current passed through the cell. The hydrogen set free on passage of current reduces the peroxide to metallic sponge lead. By this method of formation, a thin layer of active material is produced, which is porous and firmly adherent.

The other type is that in which the active material is made up in the form of a paste or powder, and applied to the grid, generally being compacted under heavy pressure. This is known as the Faure type, usually called in the trade the "pasted plate." Each method of manufacture has its advantages and each type of battery finds conditions to which it is best suited.

As has been pointed out, the capacity of a storage battery is largely dependent on the area of active material exposed to the action of the electrolyte. Therefore, the most efficient use of material requires that it be so shaped or fashioned as to give the greatest amount of exposed surface per unit mass of active material.

The electrolytic action cannot penetrate to any appreciable depth into the surface of a solid plate, and consequently that portion of the lead or lead peroxide which is acted on electrolytically must be in a finely divided or porous state, in order to present a large surface to the electrolyte.

Neither sponge lead nor lead peroxide possesses strength, rigidity or high conductivity. Mechanical considerations require the first two, and without the latter the current could not be efficiently conducted away, even if the chemical constituents of the battery were perfect. Therefore, the battery plate must consist of two parts, *i.e.*, the grid, which is a rigid framework or plate, and the active material, which is finely divided and porous lead or lead peroxide.

The grid gives the necessary solidity and strength to the plate, and also affords the required conducting path to carry current and distribute the electrical — and consequently the chemical — action evenly over the surface of the elements.

Although the action of the electrolyte cannot penetrate to any appreciable depth on a solid plate, the layer of active material may be comparatively thick, if it be porous enough to allow of the penetration of the electrolyte.

The ideal requirements to be fulfilled for the production of a satisfactory storage battery plate are:

1. The arrangement of grid and active material should be such that the current distribution is uniform over the surface of the plate. This is, of course, an impossible condition, but it can be sufficiently approached to meet all practical requirements, by proper design of grid and securing firm adherence of active material thereto.

2. The grid should be so constructed that it can expand, changing its size as the volume of the active material changes under the action of current and electrolyte. This is also difficult — in fact, with most types, impossible. Inability of designers to meet this requirement causes most of the troubles in storage batteries. The expansion on formation is very great, and the expansion and contraction of lead peroxide on discharge and charge are considerable. This requirement applies principally to the positive plate, for in ordinary working the lead of the grid or support is continuously, though slowly, oxidized, and this means a continual expansion or "growing" of this electrode. No such action takes place at the negative plate and its active material is so soft and spongy that the natural changes in volume in charge and discharge are easily taken up in the lead sponge itself.

3. Active material must be fast to the grid and in electrical contact therewith. This condition can be met when the plates are manufactured, but if the active material expands and the grid does not, and condition 2 be not fulfilled, the active material will, in time, lose both mechanical and electrical contact.

4. The grid should resist the action of the acid. This requirement is theoretically impossible, but any destructive action may be so greatly retarded as to meet all commercial demands. In types of batteries using the grid as a part of the active surface and covered with active material, this requirement does not apply.

5. The grid must be of such material that there is a minimum of local action between itself and the active material. There is no difficulty in securing this condition.

6. Ample provision should be made for diffusion of the electrolyte, so that concentration differences may equalize as rapidly as possible. This is important, especially in batteries which are to be charged and discharged at rapid rates. The importance of the ability of the electrolyte to diffuse rapidly through every portion of the active material cannot be over-estimated. Capacity, freedom from excessive sulphation, life, maintenance of electromotive force on rapid discharge, and in fact nearly every factor which goes to produce a satisfactory cell, depend on this one characteristic. It may be said that the rate of diffusion is a measure of the excellence of the electrodes.

7. The active material must expose the greatest possible surface to the electrolyte. This is effected by methods later to be described. and of which there are a large number.

Many other considerations enter into the question of producing a satisfactory cell, but the foregoing are the basically important ones. Others will further appear as the different parts are treated in detail.

CHAPTER III.

CHEMICAL THEORY OF THE LEAD CELL.

MANY theories have been advanced to account for the chemical changes in the lead cell, but the only one which has been proven by every available means, has successfully resisted every attack, and is to-day accepted by the scientific world, is the Double Sulphate theory of Gladstone and Tribe.

Gaston Planté evolved the first theory of the lead cell, which, in brief, is that on discharge the O released at the negative electrode oxidizes the sponge lead, Pb, into PbO, and the H released at the positive electrode reduces the lead peroxide, PbO_2, to PbO. Evidently he believed that the whole chemical reaction comprised the de-oxidation of the positive electrode and an equal oxidation of the negative electrode. Later, it was pointed out that the PbO_2 and Pb of the positive and negative plates both reduced to $PbSO_4$. Planté reasoned from this that the Pb and PbO_2 both changed electrolytically to PbO, and since PbO cannot exist in the presence of sulphuric acid, it was reduced from PbO to $PbSO_4$, this reduction being a secondary chemical reaction, independent of any electrolytic action.

This theory endured for a short time, until it was shown to be fallacious from thermo-dynamic considerations. When PbO is chemically changed to $PbSO_4$ by the accession of S and O, this chemical combination is accompanied by the liberation of heat, which heat is radiated and lost. Since a storage battery is reversible and gives out on discharge nearly as much energy as is put into it on charge, it is manifest that Planté's theory could not be correct.

Gladstone and Tribe, after prolonged and careful experimentation, concluded that the changes from Pb to $PbSO_4$ and PbO_2 to $PbSO_4$ are unquestionable, but instead of the electrodes being first reduced electrolytically to PbO and subsequently to $PbSO_4$ by secondary reactions, the change from Pb and PbO_2 to $PbSO_4$ is a direct one and effected solely by electrolysis, there being no secondary reaction involved.

Changes also take place in the electrolyte during charge and discharge. On charge, the SO_4, in combination with the active material and forming the lead sulphate, is given up to the liquid, which therefore gains weight and its density increases. On discharge, the converse action takes place; the SO_4 is taken up by the lead and lead peroxide to form sulphate, and the density of the liquid decreases.

These changes are set forth by the reversible chemical equations:

$$\xleftarrow{\text{CHARGE}}$$

$$(a) \ldots PbO_2 + H_2SO_4 = PbSO_4 + H_2O + O$$

$$(b) \ldots Pb + H_2SO_4 = PbSO_4 + H_2$$

$$(c) = (a) + (b) = PbO_2 + Pb + 2\,H_2SO_4 = 2\,PbSO_4 + 2\,H_2O \quad (1)$$

$$\xrightarrow{\text{DISCHARGE}}$$

Equation (*a*) expresses the reactions at the positive plate, (*b*) those at the negative and (*c*) the combined effect *which is the fundamental equation of the lead storage battery.* Read from left to right it is the equation of discharge, while if read from right to left it is the equation of charge.

The equation of charge shows that both the negative and positive electrodes start as lead sulphate, ($PbSO_4$), and, combining with the dissociated elements in the electrolyte, they turn into lead and lead peroxide, respectively. Also, SO_3 is released, which, combining with the H_2O in the electrolyte, forms sulphuric acid.

The equation of discharge shows the changes of lead and lead peroxide on the negative and positive plates, respectively, into lead sulphate, and the reduction of sulphuric acid to water.

It is not to be supposed that the reactions, as explained or given by the equation, show all the changes and transformations which occur. There are many other intermediate reactions and by-products of decomposition.

While the transformation of the Pb and PbO_2 into $PbSO_4$ is universally admitted, there are numerous theories concerning the transition from the one condition to the other, which are widely at variance, and the fact is, the chemistry of the storage battery is by no means perfectly understood.

The electro-motive force of any voltaic cell depends on the character of the metals or metallic compounds forming the elements, the kind of electrolyte and on its density or concentration. The voltage of a lead-lead battery is that between sponge lead

and lead peroxide electrodes as long as any particles of these materials are on their respective plates. Theoretically, if the elements only be considered, and the density of the electrolyte be maintained constant, the electro-motive force of a cell should be constant up to the point of reduction to sulphate of the last traces of lead peroxide and lead, and then suddenly fall to zero. As a matter of fact, the voltage falls gradually from the beginning to end of discharge, and its failure to follow the above hypothesis has been the subject of no little speculation and research.

Some investigators — notably Fitz-Gerald, Darrieus, and Griscom — have formulated a theory for the chemical reactions in a lead cell which differs somewhat from the one before given, and which is intended to explain the voltage variations and account for certain products of chemical combination which have been found to occur in storage cells.

This theory is that on passage of current, H_2SO_4 breaks up into hydrogen, (H), and sulphion, (SO_3), at the negative and positive electrodes, respectively. The SO_3 at the positive plate combines with the H_2O and H_2SO_4 of the electrolyte, forming H_2SO_4 and $H_2S_2O_8$ or persulphuric acid.

This latter compound was first observed by Bertholet in 1878 and afterwards investigated by Robertson, besides the other authorities cited.

Persulphuric acid is an unstable compound, which begins to decompose as soon as the current which produced it ceases to flow and also under the influence of heat.

At one time it was supposed to produce the large potential of a cell, when, after being fully charged, the charging current was continued, or at least to account for a large percentage of the increase above the normal potential of approximately 2 volts.

Elbs and Schönherr, however, found in their researches that persulphuric acid is formed only when charge is prolonged in highly concentrated electrolyte, *i.e.*, above 1,300 specific gravity. In electrolytes of proper density for practical storage battery work, *i.e.*, from 1,100 to 1,250, no appreciable quantity of persulphuric acid is liberated, and in any case it is not a primary product, but an accidental one. Also $H_2S_2O_8$ is endothermic and absorbs energy in formation. It therefore requires a high electro-motive force to produce it, somewhat higher than the two volts of the lead-lead peroxide couple.

Gladstone and Hibbert have shown that if persulphuric acid be added to the electrolyte at the anode, no increase of electro-motive force is observable, but on the contrary there is a slight diminution. These results were later confirmed by Mugdan.

Dolezalek shows that no irreversible chemical actions take place in a battery on charge, which would be the case if persulphuric acid were formed; and that the high voltage on charge — up to the point of gassing — and gradually decreasing voltage on discharge are due to great changes in the density of the electrolyte, which occur within the pores of the plates, these changes being far greater than those which take place in the visible electrolyte surrounding the plates.

Fitz-Gerald in 1885, and frequently since then, has maintained that on discharge the peroxide at the positive electrode is not reduced to monoxide, but to sesquioxide, Pb_2O_3, which is very close to the composition of a red lead. He admits, however, that the Pb of the negative electrode is reduced directly to $PbSO_4$ in the presence of the H_2SO_4. The subsequent transformation of Pb_2O_3 to lead sulphate, he considers a secondary action, the quantity of lead sulphate formed being independent of the quantity of electricity given out by the battery.

Gerard has proven the correctness of the Double Sulphate theory by suspending electrodes in a cell from a sensitive weighing scale and noting their increase in weight for a given number of ampere hours of discharge. This increase he found to correspond to the theoretical change as computed from the equation of the lead cell, within the limits of error of experiment and observation. Sindersten, Ayrton, Duncan, Lamb, Strecker and others have also confirmed the Double Sulphate theory in many ways.

The reactions as set forth in the fundamental equation of the storage battery do not hold, however, for abnormally excessive or very low rates of charge and discharge.

Extremely rapid charge will produce small quantities of persulphuric acid at the positive plate, while at the negative plate the H_2SO_4 is reduced to sulphur dioxide and hydrogen sulphide.

Excessive discharge rates produce so rapid a dilution of acid in the pores of the plates by the abstraction of SO_4 from the H_2SO_4, that the effect of diffusion becomes negligible. The for-

mation of sulphate cannot take place and the active materials are simply oxidized and reduced to lead hydroxide, the reaction being

$$PbO_2 + Pb + 2\,H_2O = 2\,Pb(OH)_2, \qquad (2)$$

the electro-motive force of the cell being only about one volt.

It has been found that if a lead anode, in a sulphuric acid electrolyte, be subjected to a low current density, the surface is converted into lead sulphate, and this formation of $PbSO_4$ proceeds continuously, sinking deeper and deeper into the plate and corroding it. If the current density be increased, the $PbSO_4$ is converted into lead peroxide and corrosion ceases.

This corrosion will take place in pure sulphuric acid electrolytes as well as those containing lead corroding acids. When the latter are present, the minimum current density at which corrosion takes place is much higher than if the electrolyte contain only pure dilute sulphuric acid. The current density at which corrosion stops and conversion to lead peroxide begins, is dependent also on the temperature and strength of the acid.

Also, if a couple be made up of a charged positive plate and a lead blank, and the two short circuited in an electrolyte of pure, dilute H_2SO_4, the charged plate will discharge into the lead blank and the latter will be corroded. The difference of potential between the lead blank and the electrolyte is just below that required to form lead-peroxide. If impurities are present in the electrolyte the rate of corrosion will be greatly increased.

Practically the same condition obtains between the active material of a plate and the underlying lead. This is a reason that the positive plate should not stand in a partially discharged condition.

Corrosion does not take place at all or at a very low rate if the positive plate is fully or nearly fully charged. It follows that a sulphated positive plate will be put in good condition most quickly if the charge rate is high.

It is important to note that in the rapid processes of forming Planté plates, later to be described, the current densities employed must never be high enough to cause the formation of oxygen gas at the surface of the electrode undergoing formation.

These facts and phenomena, are best explained by the hypothesis that there is a *critical difference of potential,* between positive plates and the electrolyte, above which no corrosion takes place,

and below which there is a corrosion of the lead. This hypothesis is also a consequence of the dissociation theory of electrolytes.

Gladstone and Hibbert have set forth the following results of their studies concerning the concentration of the acid surrounding the plates during the various conditions that exist in storage batteries.

On Charge.

$$2\,PbSO_4 + 2\,H_2O = PbO_2 + Pb + 2\,H_2SO_4, \qquad (3)$$

from which it is evident that sulphuric acid is formed in the pores of the two plates while the water disappears.

On open circuit, after charge, the positive electrode is composed of lead peroxide, having its pores filled with highly concentrated electrolyte, produced during charge. There are three causes which tend to produce diffusion between the electrolyte surrounding the plates and the concentrated acid in the pores. They are:

(1) Normal diffusion, which continues until the two different bodies have attained the same density, the rate of diffusion being very rapid at first and gradually diminishing as the two densities approach the same value.

(2) Local action set up between the PbO_2 of the electrode and its leaden grid or support. This produces the reaction

$$PbO_2 + 2\,H_2SO_4 + Pb = 2\,PSO_4 + 2\,H_2O.$$

That is, the acid is absorbed and replaced by water. This local action persists for a long time and tends to maintain a lower density in the pores of the active material than the density of the acid surrounding the electrodes.

(3) The chemical action of the lead peroxide on oxygenated water, which latter is formed towards the end of charge. The reaction is

$$PbO_2 + H_2O_2 = PbO + H_2O + O_2 \qquad (4)$$

PbO is chemically reduced to $PbSO_4$, which means that H_2SO_4 is used up and H_2O produced.

The last two actions are usually negligible.

At the negative electrode there is also a direct chemical action of the lead on the acid when the cell is on open circuit.

$$Pb + H_2SO_4 = PbSO_4 + H_2 \qquad (5)$$

From this it appears that acid is used up, releasing hydrogen, and thereby the density in the pores of the plates is reduced. The

equalization of density is slow and retarded by the occlusion of hydrogen bubbles in the capillary passages of the sponge lead.

On Discharge. The actions at the two electrodes are similar to those when on open circuit, with the addition of the normal reactions of discharge; $PbO_2 + Pb + 2\,H_2SO_4 = 2\,PbSO_4 + 2\,H_2O$, which shows the absorption of acid and the production of water.

As mentioned in the preceding chapter, if the discharge of a cell be carried too far, a quantity of current being taken out which is greater than that the cell is normally designed to supply, and the discharged plates be allowed to stand in the electrolyte, an excessive amount of sulphate is formed, which manifests itself by reducing the capacity of the cell, increasing its internal resistance, and shows itself visibly by a white deposit on the plates. The chemical composition of this excessive or so-called "injurious sulphate" is in no-wise different from that of the normal sulphate which is formed on discharge. Some investigators have held that the excessive sulphate does differ from the normal sulphate, but there is no ground for this belief.

Elbs theory * of the difference between the normal and the injurious sulphates is that they simply have different crystalline structures, their chemical compositions being identical. The normal sulphate exists in a very finely divided form intermixed with the Pb and PbO_2 of the two electrodes. If a discharged cell be allowed to stand idle, and temperature changes take place, even of a very few degrees, increase of temperature will cause a greater amount of lead sulphate to pass into solution in the electrolyte, while a succeeding drop in temperature will produce a deposition of some of the dissolved sulphate back on to the electrodes. This re-deposited sulphate forms on the plates and in crystals which are large as compared with the finely divided form of the original particles. In this manner an accumulation of pure sulphate in comparatively large crystals, and unmixed with any conducting material, is finally produced. This covers and clogs the pores and interposes an insulating film between part of the active material and the conducting electrolyte, which masks the electrolytic action.

If this theory be a true one, a cell discharged at a low temperature could stand idle for an indefinite length of time without injury if the temperature were slowly and continuously augmented during the period of standing.

* Die Accumulatoren, p. 40.

An ingenious though complicated theory has been evolved by Wade, termed the "polymerization" theory. This does not combat the Double Sulphate theory of Gladstone and Tribe, but may be considered as an amplification of it, taking cognizance of certain phenomena which appear contrary to the Double Sulphate theory, and reconciling them with the known fact that a portion of the active materials of the two electrodes pass from their respective active compositions to $PbSO_4$.

Wade observed that on discharge the electrodes became slightly darker in color than when fully charged, while, according to the accepted theory of mixtures, they should become lighter, as lead sulphate is white and mixtures of lead sulphate with Pb or PbO_2 are lighter in color than the unmixed active materials.

He also noted that when lead sulphate manifests itself, it shows in white deposits and is not mixed with the active materials of the electrodes. He furthermore observed the behavior of plates when reversed, *i.e.*, when, after discharge is finished, current in the direction of the discharge current is passed through the cell until the Pb of the negative plate is converted into PbO_2, while the PbO_2 of the positive plate is converted into Pb, the polarity of the plates thus being reversed. He found that in most cases, where the reversal was properly done, little or no sulphate appeared, while according to the Double Sulphate theory unmodified, the active materials on both electrodes must pass through the condition of complete conversion into sulphate. Also, the changes in the electro-motive force of a cell with variation in charge and discharge appeared always greater than could be accounted for by changes in the density of the electrolyte contained in the pores of the plates.

From these and other considerations, Wade concluded that the formation of lead sulphate did not necessarily mean that it simply mixed mechanically with the active materials, but it forms chemical compounds with them, which are feeble but, nevertheless, true compounds.

Following is a brief general outline of this theory as given by its author. Lead, like all the metallic elements, unites with other elements and radicals to form normal compounds and salts of a perfectly definite composition, such as the monoxide, peroxide, sulphate, and so forth. It also enters with greater ease than most of the metals into more complex combinations to produce basic salts (sometimes termed sub-salts), in which it is partly combined with

O or HO, as an oxide or hydrate, and partly with some other element or radical. Usually it is capable of producing not merely one, but a whole series of basic salts with each radical, of which the basic chlorides, nitrates, and acetates are well-known examples. In addition to this it is almost unique amongst the metals in the facility with which it combines with two or more different radicals other than O or HO and gives rise to curious compound salts.

But besides all its normal, basic and poly-acid salts and compounds, lead will, under suitable conditions, form others which cannot accurately be represented by any formula at all. The two most important commercial preparations of lead, namely, white lead and red lead, or minium, both furnish well-marked examples of this behavior.

Minium has no fixed or definite chemical composition. Under the action of reagents it behaves as if it were composed of lead monoxide and lead peroxide, and the formula 2 PbO, PbO_2, or Pb_3O_4, most nearly represents its average composition; but samples fully possessed of the fine scarlet colour — its distinctive physical property — have been found to approximate more closely to Pb_6O_7, Pb_4O_5, Pb_2O_3, or to some other degree of oxidation between these simpler ratios.

According to Mendelejeff, the molecules of lead may sometimes consist of a large but undetermined number of atoms, Pb_x; while, in the same way, the molecule of lead monoxide is not necessarily composed of one atom of lead and one of oxygen, PbO, but of many multiples of these quantities, Pb_xO_x; so also lead peroxide may be Pb_xO_{2x}; and so on. The assumption does not, of course, affect the percentage composition of the lead compounds as ascertained by analysis, but only their molecular weights, and these cannot be directly determined.

The behavior of certain lead compounds has always seemed somewhat puzzling, and they were at one time regarded as not being chemical compounds at all, merely intimate mixtures of other and simpler compounds. Thus, white lead was a mixture in varying proportions either of lead hydrate and normal lead carbonate, or of some definite basic carbonate with an excess of normal carbonate.

It will be evident, however, that we have only to assume a sufficiently complex molecular structure, and any number of true compounds between lead and a given set of radicals become the-

oretically possible — compounds of such closely allied composition that their physical and chemical properties grade imperceptibly from each one to the next, and so defy isolation. No doubt in some instances the whole series of compounds may be so unstable and so easily resolved into their proximate components that chemically they do appear to be nothing more than mixtures of them. In other cases only the combinations in simple ratios may possess much stability, but in every case the latter will probably be somewhat more stable and more readily formed than the remainder, which may need special conditions for their production.

The manufacture of red lead furnishes a good example of the application of the theory, and a suggestive instance of the way in which a series of compounds is brought about and of the relationship of its various terms to each other. The further oxidation of litharge by roasting at a temperature not so high as that required for its own formation does not appear to consist in the conversion of successive molecules of PbO direct to Pb_3O_4, or some other definite oxide, but in the gradual absorption of oxygen by each molecule, which takes it up atom by atom and passes through a whole series of oxides of gradually increasing richness, the action proceeding more or less simultaneously and uniformly at all parts of the mass, according to the relative adequacy of the air supply. Again, supposing the constitution of the monoxide to be $Pb_{12}O_{12}$, the series of compounds obtained may be represented as follows, but fully to account for the observed facts, its molecular composition would have to be far more complex, so as to provide numerous other oxides between each of the terms shown:

$Pb_{12}O_{12}$	12 PbO	PbO
$Pb_{12}O_{13}$	11 PbO + PbO_2	——
$Pb_{12}O_{14}$	10 PbO + 2 PbO_2	Pb_6O_7
$Pb_{12}O_{15}$	9 PbO + 3 PbO_2	Pb_4O_5
$Pb_{12}O_{16}$	8 PbO + 4 PbO_2	Pb_3O_4
$Pb_{12}O_{17}$	7 PbO + 5 PbO_2	——
$Pb_{12}O_{18}$	6 PbO + 6 PbO_2	Pb_2O_3.

The first column gives the assumed molecular composition of the oxides; the second expresses it in terms of separate molecules of monoxide and peroxide as they would appear under analysis; and the third merely shows the simplest proportional composition. Most commercial minium comes somewhere between Pb_4O_5 and

Pb_3O_4, prolonged roasting generally being required to bring it quite up to the latter proportions; but as samples are occasionally found to be still further oxidized, the series is extended to the sesquioxide Pb_2O_3.

If it be that the fully formed or charged active materials in a lead storage cell are not Pb and PbO_2, but Pb_x and Pb_xO_{2x}, that is not merely to say that the molecules are of a complex nature, physically considered, but that x atoms of lead are the smallest or unit number participating in any chemical reaction that may occur, so long as they preserve their polymeric structure intact.

On discharge, the molecules of lead at the negative electrode begin to combine with SO_4 from the electrolyte, not, however, breaking up into independent molecules of normal lead sulphate, $PbSO_4$, round a nucleus of uncombined metal, but the molecules as a whole taking part in the combination, and, as the discharge proceeds, passing through a continually changing series of sub-sulphates, without any rupture of their molecular complexity.

At the positive electrode, the reactions, though different, take place in an exactly similar manner. Oxygen is gradually abstracted and SO_4 substituted in its place, a sequence of compounds of sulphate and peroxide being produced. If it be assumed that there are twelve atoms of lead to the molecule, these two series of compounds may be represented as follows:

Pb_{12}	$Pb_{12}O_{24}$
$Pb_{12}(SO_4)$	$Pb_{12}O_{22}(SO_4)$
$Pb_{12}(SO_4)_2$	$Pb_{12}O_{20}(SO_4)_2$
$Pb_{12}(SO_4)_3$	$Pb_{12}O_{18}(SO_4)_3$
$Pb_{12}(SO_4)_4$	$Pb_{12}O_{16}(SO_4)_4$
$Pb_{12}(SO_4)_5$	$Pb_{12}O_{14}(SO_4)_5$
$Pb_{12}(SO_4)_6$	$Pb_{12}O_{12}(SO_4)_6$
$Pb_{12}(SO_4)_7$	$Pb_{12}O_{10}(SO_4)_7$
$Pb_{12}(SO_4)_8$	$Pb_{12}O_8(SO_4)_8$

But neither of these series is continued until the active material is fully sulphated and reaches the composition $Pb_{12}(SO_4)_{12}$, because lead and lead peroxide both possess a very considerable electrical conductivity; but, on the other hand, pure lead sulphate is practically a non-conductor. The active materials must therefore undergo a great change of resistance in the course of their sulphation, a change either spread more or less uniformly over the

whole discharge, or else occurring abruptly at some special stage. The latter appears to be what really happens, for we know that there is not much variation throughout the main portion of the discharge, but that the resistance begins to rise considerably towards the end, and whenever such a change of resistance takes place, it must necessarily terminate the discharge and bring about all the phenomena which do occur.

Just as fast as the resistance of the active materials, and therefore the internal resistance of the cell, rises, the potential difference at its terminals will fall away, and by the time the internal resistance has become very large in proportion to that of the external circuit, the potential difference will be reduced practically to zero. Or, to put it another way, just as fast as the resistance of the active materials rises, more and more of the electrical energy they would otherwise liberate is expended, so to speak, in their own molecules, until, when the rest of the resistances in circuit becomes relatively negligible, equilibrium is nearly established and the liberation of energy almost ceases. This is why it is impossible to push the discharge of a cell further, even by short-circuiting it; and yet on breaking circuit, *i.e.*, increasing the external resistance to infinity, the electro-motive force rapidly rises to nearly its original value.

From experiments made with chemically reduced peroxide, there seems no doubt that the critical point for the positive active material is two-third sulphation, $Pb_3O_2(SO_4)_2$, and a similar assumption, $Pb_3(SO_4)_2$, will also be adopted for the negative active material. That no more than half-sulphation is observed in practice results, no doubt, from the impossibility of uniformly discharging the active materials, especially in such types of electrodes as best lend themselves to analysis and output for weight calculations, and the above figure is probably a mean between a two-third sulphation close to the support, and a considerably less than one-half sulphation at points most distant from it.

The aggregate result, then, of the chemical changes at each electrode during a complete discharge are expressed in their simplest terms in the following equations:

At the negative

$$3\ Pb + 2\ SO_4 = Pb_3(SO_4)_2. \tag{7}$$

At the positive

$$3\ PbO_2 + 2\ H_2 + 2\ H_2SO_4 = Pb_3O_2\,(SO_4)_2 + 4\ H_2O. \tag{8}$$

But when the active materials have attained to the above compositions, it needs only to augment the electro-motive force of the discharged cell ever so slightly from an outside source, and the point of equilibrium is passed; the active materials begin to absorb energy instead of liberating it, and incipient reversal commences. In fact, in primary battery language, the cell has polarized; but, unlike other cells, at both electrodes.

If the applied electro-motive force is increased sufficiently to maintain a current through the cell — which it will do at something between 1.5 and 2 volts — full reversal then sets in. At the negative, lead is directly peroxidized; and at the positive, peroxide is directly reduced to metal, the proportion of sulphate remaining constant throughout, and the two series of compounds through which the active materials may be presumed to pass are given below, commencing with the two last terms of the previous series, which represented their composition at the end of a complete discharge.

$Pb_{12}(SO_4)_8$	$Pb_{12}O_8(SO_4)_8$
$Pb_{12}O_2(SO_4)_8$	$Pb_{12}O_6(SO_4)_8$
$Pb_{12}O_4(SO_4)_8$	$Pb_{12}O_4(SO_4)_8$
$Pb_{12}O_6(SO_4)_8$	$Pb_{12}O_2(SO_4)_8$
$Pb_{12}O_8(SO_4)_8$	$Pb_{12}(SO_4)_8$.

In this way the composition of the two active materials is exactly transposed; and, as their complex molecular structure is maintained throughout the reversal, their electrical conductivity is never interrupted, but simply remains at the comparatively low value to which it had been reduced at the end of the discharge. The following equations give the sum of the reactions during a complete reversal in the simplest terms.

At the negative

$$Pb_3(SO_4)_2 + 2\ SO_4 + 2\ H_2O = Pb_3O_2(SO_4)_2 + 2\ H_2SO_4. \tag{9}$$

At the positive

$$Pb_3O_2(SO_4)_2 + 2\ H_2 = Pb_3(SO_4)_2 + 2\ H_2O. \tag{10}$$

As the net result of these reactions is nothing more than an interchange of compounds between the anode and cathode, the cell neither furnishes an electro-motive force during this stage, nor should it, in theory, require one to be impressed on it to effect the reversal, for its potential energy is no greater at the end than at the

beginning of the process. The whole of the energy, therefore, that is expended during reversal is required to overcome the cell's inertia, or, electrically considered, its internal resistance and polarization, and the whole of it is dissipated as heat in the cell itself.

The reactions on recharge are, of course, exactly the same, whether they follow upon a reversal or, as is more usual, merely upon discharge, the difference being that the electro-motive force, direction of current flow, and composition of the active materials are reversed. In either case they consist in the abstraction of SO_4 from both active materials until they are brought back to lead and lead peroxide, just as they existed at the commencement of the discharge. The series of compounds through which this will be effected are similar to those of discharge, but now occurring in the converse order.

From this it would appear that the white irreducible lead sulphate is in reality an excess, which cannot combine with the active materials owing to their having already taken up as much lead sulphate as they can combine with.

CHAPTER IV.

THERMODYNAMIC THEORY OF THE LEAD CELL.*

In this chapter the terms "gram-molecule," "gram-molecular weight," "formula-weight" and "gram-molecules per litre" are used, which should here be defined.

The *gram-molecular weight* of any compound is equal to the sum of the quantities found by multiplying the atomic weight† of each element in the compound by the number of atoms of that element which enter into the combination. Thus, water is made up of one atom of oxygen, having an atomic weight of 16, and two atoms of hydrogen, having an atomic weight of one. Gram-molecular weight $= 1 \times 16 + 2 \times 1 = 18$. The gram molecular weight of sulphuric acid, which is H_2SO_4, is $(2 \times 1) + (1 \times 32) + (4 \times 16) = 98$.

Formula weight is *numerically* the same as gram-molecular weight, but refers simply to atomic weights.

A *gram-molecule* is one unit of gram-molecular weight, *i.e.*, a gram-molecule of H_2SO_4 weighs 98 grams; a gram-molecule of water weighs 18 grams. Concentration of acid is often given in gram-molecules per litre. This means that the number of grams weight per litre is 98 times the gram-molecules, since each gram-molecule weighs 98 grams.

The conversion formulæ for H_2SO_4 are as follows:

If G = grams weight of acid,

Gm = gram-molecular weight or formula weight of acid.

$$Gm = \frac{G}{98} \tag{11}$$

$$G = Gm \times 98 \tag{12}$$

* This chapter is only of scientific interest and its principal value is to confirm the Douple Sulphate theory. Its perusal may be omitted by readers who are interested in the engineering features only of the storage battery.

† For atomic weights see table p. 5, col. 3.

For mixtures of acid and water, in parts per litre, if Gw = weight of water in grams,

$$Gw = 1000 - \frac{G}{1.842} \text{ (approximately)}, \qquad (13)$$

in which 1.842 is the specific gravity of H_2SO_4.

$$\frac{Gw}{G + Gw} = \text{per cent of water in the mixture.} \qquad (14)$$

$$\frac{G}{G + Gw} = \text{per cent of acid in the mixture.} \qquad (15)$$

$$Gw = 1000 - \frac{Gm \times 98}{1.842} \qquad (16)$$

The following table gives the relations between percentage of H_2SO_4, the grams per litre, and the gram molecules.

TABLE II.

Per cent of H_2SO_4.	Grams per litre.	Gram. mols.
10%	106.9	1.09
15	116	1.18
20	229	2.34
25	296.5	3.03
30	367	3.74
35	443	4.52
40	523	5.35
50	700	7.15
60	903	8.85

Bertholet has shown that the electro-motive force necessary to decompose a substance electrolytically, is proportional to the quantity of heat absorbed by the decomposition per gram-molecule (or other unit mass), of the substance, and, conversely, the electro-motive force produced by a voltaic couple is proportional to the quantity of heat released by the chemical reactions which take place in the cell. Unfortunately, the heat of formation of but few substances is known accurately, and therefore most computations based on chemical thermo-dynamics are only close approximations.

If J = quantity of heat expressed in calories, liberated by the combination of a unit weight of either ion entering into the combination, and C = the electro-chemical equivalent of the ion, which is the number of grams of the ion set free per coulomb of electricity, then the heat liberated for C grams is CJ calories.

Since a calorie is equal to 3.1 foot pounds, or 4.24 volt-coulombs, the heat energy required to liberate C grams is = 4.24 CJ volt-coulombs or Joules.

In the case of hydrogen, the quantity set free per coulomb is 4.24 × 0.00001038 J = 0.0000436 J. Call this quantity N.

For any other substance, the quantity of heat liberated will be equal to NC calories, in which C is the electro-chemical equivalent of the substance, that of hydrogen being unity, as explained in Chapter I.

If Q coulombs pass through the cell, the heat liberated will be NCQ volt coulombs and the total energy W = NCQ. This is also equal to QE, in which E is the electro-motive force required to send Q coulombs of electricity through the cell.

Since QE = NCQ, E = NC. If the heats of formation of different substances are known, E is easily calculable. The heat released, J, is the *net* energy set free, inclusive of all reactions that take place.

There may be several different reactions and some of the compounds may be endothermic, while some are exothermic, therefore some of the reactions may give out heat energy, while other reactions will absorb heat. The net heat energy available which is transformed into electrical energy is the difference between the sum of all the heat units given out by the processes which liberate heat, minus the sum of the heat units absorbed by all the reactions which absorb heat. This simple thermo-dynamical relationship between heat and electrical energy does not cover all the conditions however. The electrolyte in the cell may absorb a certain amount of heat, which energy will be expended in a rise of temperature and lost in radiation, thereby reducing the electrical energy available from a given chemical combination. The converse of this condition may also obtain and the electrical energy taken from a cell may be in excess of the heat energy of the chemical combination, in which case heat is abstracted from the medium surrounding the electrodes, and the cell temperature is lowered.

An accurate mathematical relationship between the thermal and electrical quantities involved requires, therefore, the addition of another term to the equation which shall cover the temperature changes in the cell.

The following analysis is due to Helmholtz.

Total change of energy which accompanies a chemical reaction

is equal always to the heat liberated or absorbed by the reaction if carried on at constant temperature. That amount of heat of reaction which is changed into electrical energy is called the " free energy " of the reaction.

If Q = the total heat effect of a reaction,
W = changed in free energy, or the available work,
T = absolute temperature of the cell, then,

$$W = Q + T\frac{\partial W}{\partial T}. \tag{17}$$

$\frac{\partial W}{\partial T}$ is the *temperature coefficient* of the couple.

If the heat effect be based on one gram equivalent of the reacting element, W will be equal to that electrical energy corresponding to one gram equivalent of the substance which causes the reaction.

Faraday found that 96,540 coulombs produce the reaction of one gram equivalent of monovalent chemical substances, and if E = electro-motive force accompanying the reaction,

$$W = 96{,}540 \times E, \text{ volt-coulombs.} \tag{18}$$

Since one volt coulomb = 0.239 gram calories.

Whence $$E = \frac{W}{23073}.$$

$$W = E \times 96{,}540 \times 0.239 \text{ gram calories.}$$

Since $$W = Q + T\frac{\partial W}{\partial T},$$

$$E = \frac{Q + T\frac{\partial W}{\partial T}}{23073} = \frac{Q}{23073} + T\frac{\partial E}{\partial T}. \tag{19}$$

The first right hand term of the equation indicates the " heat effect of the reaction," and is known as "Thomson's Law," while the second right hand term is the temperature coefficient of the cell, derived by Helmholtz.

The temperature coefficient, $\frac{\partial E}{\partial T}$, is the change in voltage, for a given couple, for each degree change in temperature, T being the absolute temperature which, for a room at ordinary temperature of 18 degrees C., is 273 + 18 = 291 degrees C.

The temperature coefficient of the lead cell varies with the electrolyte density, being zero at a density of 1.044 (at 15.5 degrees C.) and having a positive value with electrolytes of higher density, while for densities below 1.044 the value is negative.

For example, if the temperature coefficient of a cell is .0003 volt the amount to be added to the electro-motive force as determined from the heat of formation to give the actual electro-motive force will be $.0003 \times 291 = 0.0873$ volt, assuming a cell temperature of 291 degrees C. absolute.

It has been found that at the ordinary electrolyte densities in practice, the temperature coefficient is negligible.

Therefore for practical work

$$E = \frac{Q}{23073} \text{ volts.} \tag{20}$$

It must be remembered, in computing the net total heat, Q, that in addition to the chemical reactions at the electrodes, heat is either released or absorbed in the electrolyte with increase or decrease in dilution. As is well known, the mixing of H_2SO_4 and water is accompanied with the liberation of heat, and, conversely, a change in concentration from one density to a higher one, which is the equivalent of abstraction of water from the electrolyte, requires the absorption of heat, and therefore a decrease in temperature of the electrolyte results.

The heat of formation of compounds is given in two different ways, depending on whether a unit of formula weight of the compound or the combining weight of the substances which would react with a single combining weight of hydrogen is adopted. The former the author considers the simpler, and it is more generally used, and it will therefore be adopted in this discussion.

Obviously, the heat of formation of a substance depends on the form of the combining substances and the stages through which they have been carried from their elemental condition before the final combination takes place.

Thus H_2SO_4, when made by the combination of the proper proportions of H, S, and O, has a heat of formation of 192,930 calories per unit formula weight, *i.e.*, 2 molecules of hydrogen = 2 grams, one molecule of sulphur = 32 grams, and 2 molecules of oxygen = 64 grams, making a total formula weight of 98 grams.

It is customary to show the character of the substances which combine to form a given compound by separating the chemical formula into divisions by commas. Thus H_2SO_4, made up from H, O, and S, would be written H_2, S, O_4.

If made up of H_2, O, and SO_3 the formula is written H_2, O, SO_3 while if made up of sulphur trioxide and water, it is written H_2O, SO_3.

If H_2SO_4 be made up of H_2, O, and SO_3, *i.e.*, 2 grams of H, 16 grams of O, and 80 grams of SO_3, written $[H_2,O,SO_3]$ the heat of formation is less than 192,930 calories, because a portion of the combination had taken place before the final composition. The value in this case is 89,680 calories.

Again, if it be made up of 18 grams of water and 80 grams of SO_3, written $[H_2O,SO_3]$, the heat of formation is less than that in the immediately preceding example by an amount equal to the heat of formation of water, because in making the compound the O and H are used which have been combined before the final combination is effected.

The heat of formation of one formula weight, *i.e.*, 18 grams, of water is 68,360 calories. Deducting this from the 89,680 calories as before given, the remainder is 21,320 calories, which is the heat of formation of 18 grams of water with 80 grams of SO_3.

The symbol Aq denotes a comparatively large amount of water in a solution, the quantity being indefinite but not indefinitely great. For example, H_2SO_4 Aq = 17,860 calories denotes the heat of mixture of one formula weight of acid (98 grams) with a comparatively large quantity of water.

Reverting to the formula, $E = \frac{Q}{23073} + T\frac{\partial E}{\partial T}$, and neglecting for the moment the temperature coefficient of the equation, it appears that for a heat of formation of 23,073 calories, or in round numbers 23,000 calories, one volt will be produced. This also corresponds to the formula E = NC, in which N = 0.0000436, H = $\frac{H}{23073}$, C disappearing when equal to unity, as in the case of hydrogen. These constants refer, however, to the heat formations of a unit quantity of the compound in which one gram equivalent of hydrogen is incorporated. Thus the heat of formation of water is 68,360 calories for 2 molecules of H and one of O, making the

formula weight 18 grams = $2 \times 1 + 16$. For the equivalent of a single molecule of H, both the formula weight and the heat of formation would be half this, or 9 grams and 34,180 calories respectively. If the heats of formation of formula weights are taken, the calories, per volt, will be double the previously given figures, or 46,000 calories, for the reason that oxygen is the element which is added to or taken from the compounds in a cell, and this being bi-valent, requires two molecules of hydrogen to combine with it and the amount of 23,000 calories per volt is based on a single gram equivalent of hydrogen. In reality, the general formula for the electro-motive force of a cell is $E = \frac{Q}{23073 \times V} + T\frac{\partial E}{\partial T}$, in which V is the valency of the combining element, and since that of oxygen is 2, the formula for any cell (neglecting the temperature coefficient) is $E = \frac{Q}{46146}$ or, in round numbers, 46,000 calories produce one volt where the heats of formula weights are used. Of course either system will lead to the same result, it being merely a question of the unit adopted.

Following are the heats of formation of various substances per unit formula weight. Note carefully the location of the commas, which show the state of the substances combining.

TABLE III.

H_2, O	= 68,360	calories.
H_2, S, O_4	= 192,930	"
H_2, O, SO_3	= 89,680	"
H_2, SO_4	= 89,680	"
H_2O, SO_3	= 21,320	"
Pb, SO_4	= 112,970	"
Pb, O_2	= 62,300	"

The heats of dilution of the acid with the water have been determined by Thomsen and are given by the formula:

$$\text{Calories} = \frac{a \times b}{b + 1.798\,a} \times 17860 \qquad (21)$$

in which, a = gram-molecules of acid in the mixture and b = gram-molecules of water.

The curve shown in Fig. 2 gives the heat of dilution for various percentages of water by weight with one gram-molecule of acid. The actual weight of H_2SO_4 is 1.842 times that of water. The formula weight, however, of H_2SO_4 is 5.45 times that of water, the formula weight of water being 18 and of acid 98. Obviously, to make a 50% mixture, by weight, to 98 grams of acid, there must be 98 grams of water, which according to formula weights means 5.45 parts of water to one of acid.

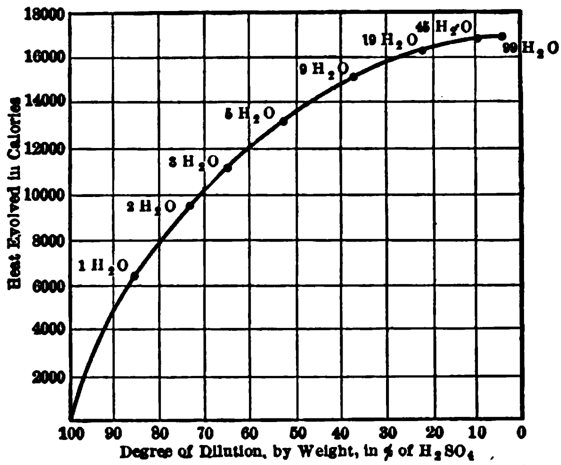


FIG. 2. Heat of Dilution of H_2SO_4.

In order to make the curves available for formula or gram-molecular weight computations, a few points are marked on the curve giving the number of parts of water to one part of acid by formula weight.

To reduce percentages of mixtures by actual weight to parts of water, gram-molecular weight per gram-molecular weight of acid, divide the percentage of water by the percentage of acid and multiply the quotient by 5.45. The result will be parts of water per part of acid in gram-molecular weights.

For example, in ordinary electrolyte there are usually about 27% acid and 73% water.

This corresponds to $\frac{73}{27} \times 5.45 = 14.75$ parts of water to one part of acid referred to gram-molecular weights.

Having these data it now becomes possible to compute the electro-motive force of a lead cell.

$$2\,PbSO_4 + 2\,H_2O = Pb + PbO_2 + 2\,H_2SO_4.$$

$$2\,Pb,SO_4 + 2\,H_2,O - Pb - Pb,O_2 - 2\,H_2,SO_4 = \text{calories liberated.}$$

$$Pb,SO_4 = 112{,}970 \text{ calories: } 2\,Pb,SO_4 = 225{,}940 \text{ calories.}$$

$$H_2,O = 68{,}360 \text{ calories; } 2\,H_2,O = 136{,}720 \text{ calories.}$$

$$Pb,O_2 = 62{,}300 \text{ calories.}$$

$$H_2,SO_4 = 89{,}680 \text{ calories; } 2\,H_2,SO_4 = 179{,}360 \text{ calories.}$$

Adding the positive quantities together their sum is 225,940 + 136,720 = 362,660 calories, and the sum of the negative quantities is 62,300 + 179,360 = 241,660 calories. Deducting the negative sum from the positive, the net heat of formation is 121,000 calories. $E = \frac{121000}{46000} = 2.63$ volts, which is the potential for electrodes immersed in pure acid, the temperature coefficient being neglected. The usual electrolyte, however, contains about 27% acid, by weight.

From the curve Fig. 2, the heat of dilution for this ratio of acid to water is 16,000 calories per unit of acid, which must be deducted from the value above computed. Since there are two molecules of acid, the net calories will be 121,000 − 2 (16,000) = 89,000 calories. $\frac{89000}{46000} = 1.935$ volts. This assumes, of course, all the active material being in its pure state, unmixed with sulphate. Wade shows that another factor enters into the problem, namely, the additional heat of dilution, due to the fact that 2 × 14.75 or 29.5 molecules of water in solution in the electrolyte have been set free by the absorption of 2 molecules of H_2SO_4 and an additional 2 molecules of water again released by the chemical combination of 2 molecules of SO_3, leaving behind the 2 molecules of H_2O.

This makes a total of 31 molecules of water which are released to further dilute the acid and cause a corresponding production of energy which will go into the form of electrical energy. Wade computes an approximate additional heat of dilution from this small quantity of water as 2,000 calories, on the assumption of a large quantity of electrolyte which has its density changed but little by this additional dilution.

2,000 calories = 0.043 volt, which added to the previously computed 1.935 makes a total of 1.978 volts.

Another corrective factor is the temperature coefficient. For

the acid concentration of 27% of acid to 73% of water, the temperature coefficient, $\frac{\partial E}{\partial T}$, is 0.0003 volt per degree C.

At normal room temperature of 291 degrees C. (absolute) the voltage due to the temperature coefficient is 0.0003 × 291 = 0.0873 volt. The actual computed electro-motive force is therefore 1.978 + 0.0873 = 2.0653 volts.

The temperature coefficient has been the subject of considerable investigation by Streintz. The results of his researches are given in the accompanying formula, table and curve.

The formula for the value of the temperature coefficient is:

$$\frac{\partial E}{\partial T} = (357 \times 10^{-6}) - 0.64 \times (E - 1.998)^2 \qquad (22)$$

The measurements made by Streintz are given in Table IV.

TABLE IV.

VALUES OF TEMPERATURE COEFFICIENT × 10^6.

E (observed).	$10^6 \frac{\partial E}{\partial T}$ (observed)	$10^6 \frac{\partial E}{\partial T}$ (calculated).
1,9223	140	....
1,9828	228	213
1,9860	274	265
1,9920	333	335
2,0031	335	341
2,0072	312	305
2,0084	285	293
2,0090	279	280
2,0105	255	265
2,0779	130	....
2,2070	73	....

For actual values of $\frac{\partial E}{\partial T}$ divide by 10^6.

In the first column are the values of the observed electro-motive force, the second column shows the observed temperature coefficients, while the third column shows the temperature coefficient as calculated from the formula. It is, of course, understood that the different electro-motive forces tabled in the first column are for different densities of electrolyte.

All observations were made at a temperature of 10 degrees C.

The curve, Fig. 3, shows the variation in temperature coefficient for varying electrolyte densities. As may be seen, the coefficient at a density of 1.044 (= 6.5% acid) is zero. Above this density its value rises rapidly until it reaches a maximum of 0.000341 volt per degree C. at a density of 1.160, after which it begins to decrease slowly with the density.

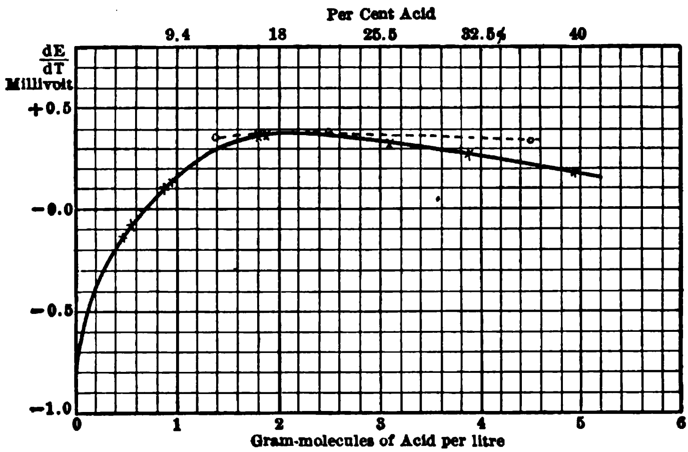


FIG. 3. Temperature Coefficients for Various Electrolyte Densities.

Below the density of 1.044, the temperature coefficient increases from zero rapidly but in a negative direction. This means that at electrolyte densities less than 1.044 the voltage of a cell decreases with increase of temperature, while with densities above 1.044 the electro-motive force increases with increase of temperature.

In practical work, however, the density is universally above the neutral value of 1.044 and hence $T \frac{\partial E}{\partial T}$ is additive. A positive temperature coefficient means that a cell heats during charge by an amount greater than the I^2R loss would produce, an additional amount of heat being released, while on discharge the cell does not heat as rapidly as would normally result from the I^2R loss, there being a counter cooling effect which, in some cases, over counterbalances the I^2R heating and actually produces a reduction in temperature of the cell while current flows through it. This phenomenon was first investigated by Dr. Louis Duncan and H. Wiegand, in 1889.*

* Transactions A. I. E. E., 1889.

The temperature coefficient may be computed from the general equation of Helmholtz:

$$E = \frac{Q}{23073} + T\frac{\partial E}{\partial T}$$

$$\frac{\partial E}{\partial T} = \frac{E}{T} - \frac{Q}{23073 \times T}. \qquad (23)$$

For very dilute acids,

$E = 1.92 + 0.15 \log C$, volts, in which C = concentration of the electrolyte in gram-molecules per litre.

Since
$$\frac{\partial E}{\partial T} = \frac{E}{T} - \frac{Q}{23073 \times T},$$

the value of the temperature coefficient at 18 degrees C. or 291 degrees C. absolute will be:

$$\frac{\partial E}{\partial T} = \frac{1.92 + 0.15 \log C}{291} - \frac{Q}{23073 \times 291},$$

which reduces to

$$\frac{\partial E}{\partial T} = 0.000517 \log C + 0.00584 - \frac{Q}{6710000} \text{ volts per degree,}$$

or

$$\frac{\partial E}{\partial T}\ 0.517 \log C + \left(5.84 - \frac{Q}{6710}\right) \text{millivolts per degree.}$$

The portion of the right-hand term of the equation in parenthesis is a constant, independent of the concentration. The equation may therefore be written:

$$\frac{\partial E}{\partial T} = 0.517 \log C + (\text{Constant}), \text{ millivolts per degree.}$$

These equations hold for values of C not below 0.0005 nor above 0.1 gram-molecules of acid per litre, the latter figure corresponding to a density of 1.007, showing that these formulæ apply only to extremely dilute solutions.

CHAPTER V.

THE QUANTITY AND DISTRIBUTION OF ACTIVE MATERIAL.

THE weight of peroxide or sponge lead necessary for a given output depends on

(1) The disposition of the active material.
(2) Its density.
(3) Its thickness.
(4) The rate of discharge or current density per unit area of the electrolyte between the plates.

The theoretical weight of metallic lead required on either element to form sufficient active material for one ampere hour of discharge is 3.86 grams = .135 ounces avoirdupois, which will weigh .156 ounces when converted into peroxide. This theoretical quantity is calculated from the fundamental equation $Pb + PbO_2 + 2\ H_2SO_4 = 2\ PbSO_4 + 2\ H_2O$. In practice, however, the weight of active material per element is from 3 to 6 times the theoretical, for the reason that it is impossible to reduce all the active material or cause every particle to be penetrated by the current. Experiments of Fitz-Gerald, Reckenzaun and Sellon show that from .50 to .80 ounce of spongy lead is required per ampere hour, and from .53 to .86 ounce of metallic lead converted into peroxide for the same capacity. Fitz-Gerald states that the latter figure is required only when the contact between conducting grid and material is defective. As a matter of fact, when certain portions of the peroxide or sponge lead are not in contact with the grid, those portions become inactive and should no longer be classed as active material. If sections of the layer should be removed at those spots where it had lost contact, the capacity of the plate would be practically unchanged and the weight of the active material decreased. Any figure, therefore, based on defective contact, is erroneous, as it leads to infinity as a limit when the contact is totally eliminated.

Wade gives a table of outputs of pasted electrodes as follows:

TABLE V.

Ratio of active material to support.		Ampere hours output of electrode.			
By weight.	By volume.	Per lb.	Per kilo.	Per cu. in.	Per cu. cm.
1 to 4	1 to 2	6.0	13	2.0	0.110
1 to 2	1 to 1	10.0	22	3.0	0.165
1 to 1	2 to 1	15.0	33	4.0	0.220
1½ to 1	3 to 1	18.0	40	4.5	0.250
2 to 1	4 to 1	20.0	44	4.8	0.265
2½ to 1	5 to 1	21.0	47	5.0	0.277
3 to 1	6 to 1	22.0	50	5.3	0.286
4 to 1	8 to 1	23.5	52	5.4	0.300

The capacity obtainable from a given amount of active material is stated, by one authority, to be about 30 ampere hours per pound, which is in (approximate) accordance with the figures in the above table.

Fitz-Gerald gives the following practical rule for weight of active material per ampere hour for each of a pair of plates:

TABLE VI.

Long discharge,	8 to 10 hours	....	.53 oz. avoir.
Moderate "	5 "	....	.60 " "
Quick "	3 "	....	.70 " "
High rate "	2 "	....	.80 " "
High rate "	1 "	....	1.00 " "

All the weights given by the three above cited authorities are for discharges, which at the 8 hour rate end when the voltage falls to 1.80 and at the higher rates end at about 1.70 volts.

Fitz-Gerald explains the necessity of increasing the amount of active material with increase of discharge rate, by the fact that a battery, having a given weight of active material on the plates, will deliver fewer ampere hours at high rates than at low rates of discharge, and therefore an increase of active material is required for high rates if the capacity is to remain constant.

With this theory the author cannot agree, as decreasing capacity at high discharge rates is caused by several factors which are related to current density, exposed surface and electrolyte circulation rather than to the absolute quantities of peroxide and lead sponge present.

On rapid discharge, the inability of the acid to circulate from the surrounding liquid to the inside of the pores soon brings down the voltage to the minimum allowable value before the normal capacity has been expended. Also the loss from internal resistance is increased.

As is well known, a battery which has been rapidly discharged has extraordinary recuperative power. If it be allowed to stand a short time a further discharge may be taken from it which will be greatly in excess of the recuperative discharge if the cell be first discharged at a low rate.

These considerations lead to the conclusion that the increasing of active material without increasing the area over which it extends would in no wise produce a proper plate for rapid discharges, for it would increase the thickness of the active material, while a thin layer is most suitable for rapid discharge rates. The same quantity of active material spread over a greater surface would be more nearly in accordance with the requirements of the case.

Sieg, Jumau and others have made experiments to determine the influence of the thickness of the layer of active material on the capacity, per unit weight, under varying rates of discharge. As will be seen later, the initial density of the electrolyte is also a modifying factor and this does not appear to have been considered in these researches. The net results indicate conclusively that the capacity per unit weight of active material falls off with the increase in thickness of the layer, and the higher the rate of discharge, the greater is this diminution. At very low rates the capacity per gram of active material decreases but little with an increase in its thickness, but at normal and high rates the decrease is very great.

The author considers $\frac{1}{16}$ to $\frac{3}{32}$ of an inch the best thickness for active material when pasted on grids and subjected to 4 to 6 hour discharge rates. This thickness means of course the distance from the surface of the active material to the supporting and conducting grid.

It is of interest here to note the ratios of the weight of active material to weight of elements in the various types of batteries on the market.

The capacity per pound weight of elements is from 2.5 to 4 ampere hours in station batteries and from 4 to 6.5 ampere hours

for traction cells. Allowing for pasted plates .56 ounce weight of lead converted into active material and an increase in weight of 15.5 per cent when changed into active material, this would make $.56 \times 1.155 = .644$ ounce, active material per ampere hour on each plate which for both plates = 1.288 or say 1.3 oz. = .08125 pounds active material total in the battery per ampere hour.

Assuming 2.5 ampere hours per pound of element, there would be $.08125 \times 2.5 = .221$ pounds active material per pound of element, or 22% of the total weight would be active material. Similarly, in a cell delivering 4 ampere hours per pound of element, the percentage of active material is 32.5% and in one delivering 6.5 ampere hours per pound, the percentage is 52.8%.

The weight of active material on Planté plates is about 25% less than these amounts for low rates and 40% less for high rates. The durability of electrodes will be greater the less the capacity per pound weight. Where the capacity per pound of cell is high, the layer of active material must be very thick, the quantity of electrolyte small and its density high. These two latter conditions are detrimental, as will be presently shown.

Of course, the greater the weight per ampere hour of capacity the greater is the cost of the battery and therefore battery durability must be paid for.

A given weight of metallic lead will form 1.155 times its weight of lead peroxide or will increase 15.5%. Conversely to produce a given weight of peroxide .866 times or 86.6% of the given weight of metallic lead is required.

$$PbO_2 \times .866 = Pb$$
$$Pb \times 1.155 = PbO_2.$$

Similarly the relations between lead oxide (litharge) and metallic lead are

$$Pb \times 1.075 = PbO$$
$$PbO \times .93 = Pb$$

and between red lead (minium) and metallic lead

$$Pb_3O_4 \times .906 = Pb$$
$$Pb \times 1.104 = Pb_3O_4.$$

For weight of lead peroxide reduced to litharge or the converse, the following will be the relation:

$$PbO_2 \times .937 = PbO$$
$$PbO \times 1.067 = PbO_2.$$

If lead peroxide be converted into lead sulphate or vice-versa, the changes in weight become

$$PbO_2 \times 1.275 = PbSO_4$$
$$PbSO_4 \times .785 = PbO_2.$$

The volumetric relationships cannot be given, as these vary with the molecular structure of the substances. Wade gives as the weight of active materials from 2 to 4 ounces per cubic inch, varying with the degree of compression and density.

Lead peroxide has usually a weight of 3.25 ounces avoirdupois per cubic inch, which is just one-half the weight of lead, the latter having a weight of 6.5 ounces per cubic inch.

Following is a table of ordinary densities of lead and its principal compounds.

TABLE VII.

Substance.	Symbol.	Sp. grav.
Lead (metallic)	Pb	11.4
Red lead	Pb_3O_4	8.9
Litharge	PbO	9.3
Peroxide { hydrated	PbO_2	7.0
Peroxide { anhydrous	PbO_2	9.4
Lead sulphate	$PbSO_4$	6.2

As has been indicated and will be more fully discussed later, it is important that the active material be of a porous character so that the electrolyte may easily penetrate to every particle of the substances on the electrodes and the diffusion of acid into and out from the pores be as easy and rapid as possible. There are methods of artificially augmenting the porosity which are set forth in those chapters treating of the formation and production of storage cells.

The resistance of active materials is low. That of sponge lead is substantially the same as metallic lead, increased somewhat by its porosity. The resistance of PbO_2 is considerably higher. Shields has found that PbO_2 compressed and dried at 100 degrees C. has a resistance of about 0.5 ohms per cubic centimeter, which is six times the resistance of electrolyte at normal working densities. When hydrated, chemically cohesed and saturated with electrolyte, its resistance must be far lower than the above amount and probably more nearly approximates 0.1 ohm per cubic centimeter.

CHAPTER VI.

THE ELECTROLYTE.

THE electrolyte must be of sulphuric acid made from sulphur. Acid made from pyrites should never be used as it contains injurious substances.

It should be diluted with sufficient pure, distilled water to bring to the required density, the acid in every instance being poured into the water, and never the water into the acid. The reason of this is that on dilution a chemical combination is formed and not a mere mechanical mixture, and heat being liberated, the liquid becomes hot. (See Chapter III.) If the water be poured into the acid, the chemical combination between the larger quantity of concentrated acid is more rapid than if the reverse method be pursued and the acid be poured into the water.

It has become customary for sulphuric acid manufacturers to produce a low concentration acid, especially for electrolyte, and they claim that this is superior to that made by mixing in small quantities at the point of using. That it is more convenient, more likely to be of exactly the proper density, and carefully prepared is obvious, but electrolyte mixed on the spot is often cheaper, both as to original cost and transportation, the weight being over three times as great for the dilute electrolyte as for an equivalent quantity of concentrated acid.

The vessel in which the mixing is done should be of glass, glazed earthenware or lead, and the liquid should be stirred with a clean wooden stick, the acid being added to the water slowly. The mixture must be allowed to cool before pouring into the cells.

After cooling, the specific gravity will be found greater than while hot, and the careful addition of a little water may be necessary to bring the liquid to a proper density.

The amount of dilution or specific gravity of electrolyte, when the batteries are fully charged, should be about 1.190 to 1.225 at 60 degrees F. for power station cells, though in motor car batteries densities of from 1.270 to 1.300 are often used.

The abstraction of the SO_4 on discharge which combines with the lead oxide to form lead sulphate, causes a gradual diminution of the specific gravity of the liquid by a definite amount, as has been shown.

The final density on discharge should not fall below 1.150, and 1.170 to 1.195 is usual practice.

The density of the electrolyte has an important bearing on the operation of the battery. If it be too high, excessive sulphation is facilitated and the plates are liable to rapid depreciation. The electro-motive force of a battery, however, varies with the density of electrolyte, as will be later shown. (See Chapter VII.)

The resistance of dilute H_2SO_4 is least at a density of from 1.224 to 1.240, rising if the gravity be either increased or decreased.

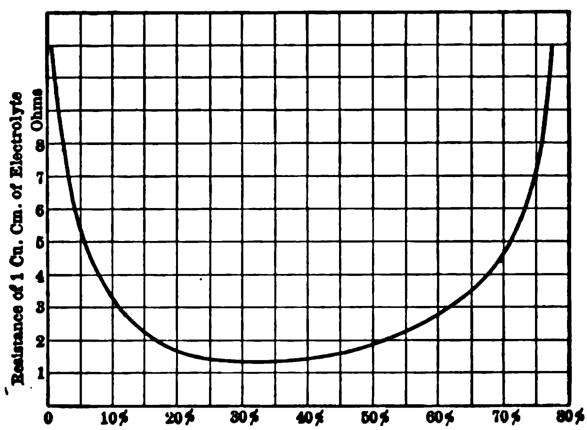


FIG. 4. Variation in Electrolyte Resistance with Density at 60 deg. F.

Figure 4 is a curve of variation of electrolyte resistance with density, and Fig. 5 gives also the resistance at various densities and four different temperatures, but shows only the working portions of the curves. These curves show that the temperature coefficient is negative, the resistance decreasing with increase of temperature.

The electrolyte should be free from chlorine, nitrates, acetates, organic substances, iron, copper, arsenic, mercury and the slightest trace of platinum. Mercury alone has no injurious effect unless it be present in sufficient quantity to amalgamate the plates, but

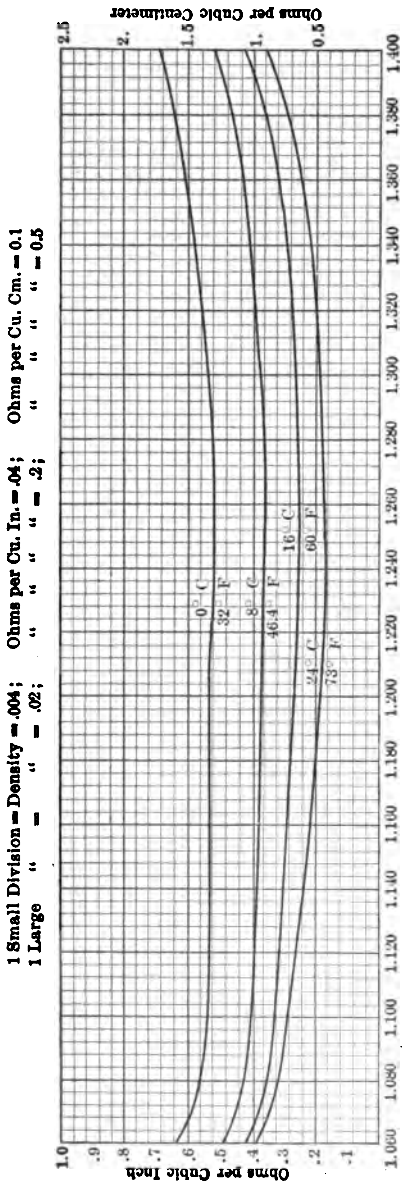


FIG. 5. Variation in Electrolyte Resistance with Density and Temperature.

in combination with another metal may cause local action, as explained in Chapter X.

Heinz gives the following as the limiting values of the percentages of iron, chlorine and nitrogen allowable in good electrolyte, concentrated acid being 100%; iron, .01%; chlorine, .002%; nitrogen, in any form, as ammonia, nitric acid, etc., .01%.

The electrolyte should be tested for impurities before putting into batteries and also, occasionally after being in use.

If no objectionable elements are revealed on the first tests, and later nitrogen, chlorine or acetate is found, it may be assumed that the acids used in formation were not thoroughly removed.

The following tests are sufficient for the determination of the suitability of the acid or electrolyte for battery purposes:

Platinum.

A chemical test for traces of platinum is so complicated and difficult as to make it practically impossible for anyone but an experienced chemist to carry it through, and if the electrolyte be suspected, a sample should be analyzed by some one having the necessary skill and appliances.

A good rough test for traces of platinum is to pour the electrolyte into a cell in which the regular battery plates are immersed. If gassing takes place for some time on open circuit, it is an indication of the presence of platinum.

Since the smallest trace will cause discharge of the negative electrodes, and the higher grades of acid are often refined in platinum stills, great care must be used to procure electrolyte which is free from it.

Iron.

Take a sample of dilute acid — about one part of acid to two of water — and neutralize with ammonia or caustic potash solution. Then boil with hydrogen peroxide or a few drops of nitric acid, using a quantity of about one-thirtieth the amount of the solution being tested. All iron present is changed into the ferric state. Take now a sample of the liquid and put into a test tube. Add ammonia or caustic potash solution until the mixture becomes alkaline. If there is much iron present a brownish red precipitate will form on making the liquid alkaline.

A second test should be made for traces of iron, which is done by taking a second sample of the liquid which has been neutralized

and boiled with hydrogen peroxide, and adding a few drops of red prussiate of potassium, (KCNS). If any traces of iron are present the liquid will turn red. This is a very delicate test.

Chlorine.

To the dilute acid, add a few drops of nitrate of silver solution made by dissolving 20 grams of silver nitrate in 1000 cu. cms. of distilled water. If chlorine is present, as chlorides, the solution will turn white, owing to the formation of a precipitate of silver chloride.

This precipitate is milky when only a small percentage of chlorides is present, and curdy when there is a considerable quantity of these impurities in the liquid. The precipitate may be re-dissolved by adding enough ammonia to neutralize the liquid, after which it may again be precipitated by the addition of a few drops of nitric acid. An excess of silver nitrate will cause the formation of a granular white precipitate which falls to the bottom of the test tube. This is no indication of any impurity but is simply a precipitate from the silver nitrate itself.

Nitrates.

1. Put 25 cu. cms. of 50% dilute acid in a test tube, and add 10 grams of strong ferrous sulphate solution freshly prepared by dissolving crystals in cold water. Carefully pour down side of a test tube 10 cu. cms. of chemically pure, concentrated sulphuric acid.

If nitric acid be present, it will be indicated by a stratum of a brown color which will form between the solution and the concentrated acid. The depth of the color will indicate the relative proportion of nitric acid present. If dilute electrolytes are being tested, enough concentrated sulphuric acid should be added to make the dilution approximately 50%. All liquids used must be cool. This is not a delicate test; a better one is as follows:



Fig. 6.
Test for Nitrates.

2. If the electrolyte be first tested for chlorine and found free of it, place some chemically pure copper filings in a test tube and pour in the electrolyte to be tested. Close with a stopper through which is passed a glass tube having a double bend, as shown in Figure 6.

Solution of ferrous sulphate is poured into the bend of the tube as indicated at "B."

On heating the tube over a bunsen flame, the nitrate vapors will attempt to pass out of the tube, but will be absorbed by the ferrous-sulphate, which latter will turn to a blackish brown.

Copper.

Ammonia solution added to the electrolyte produces a bluish-white precipitate if there is any copper present. When an excess of ammonia is added and the liquid becomes alkaline, the precipitate disappears and the liquid becomes a dark blue color. This is a delicate test, and will show the presence of 0.002% of copper.

A more delicate test is to add a few drops of potassium ferrocyanide to the electrolyte under test. A reddish brown color indicates traces — down to 0.0001% — of copper. The deeper the color the greater is the amount of copper in the solution. A reddish brown precipitate indicates a considerable amount of copper.

Mercury.

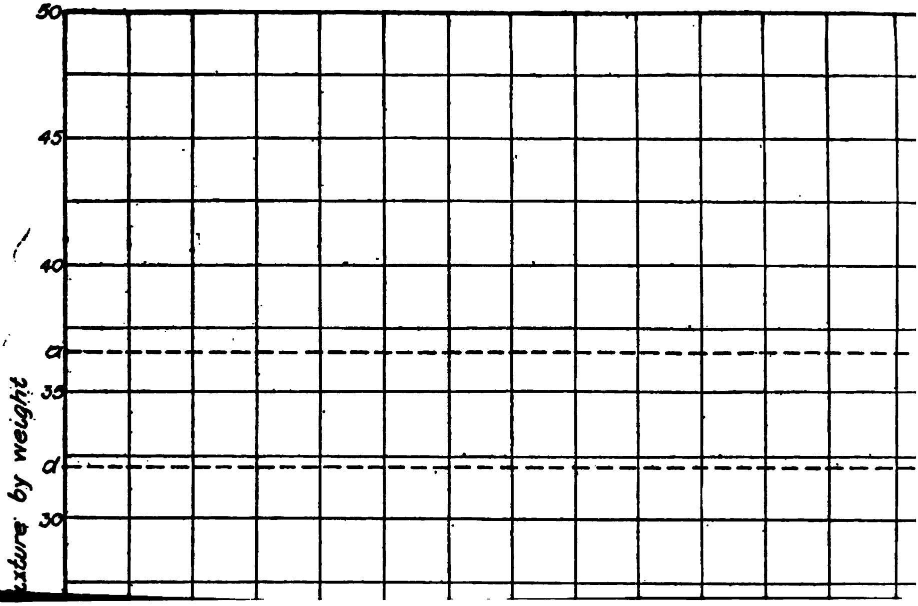
The presence of mercury in the electrolyte is indicated by a black precipitate when lime water is added, or by an olive green precipitate if solution of potassium iodide be added.

Arsenic.

There are several tests for arsenic. (1) Reinisch's test is one of the simplest and consists in diluting a small amount of the acid to be tested with about 80% distilled water then adding from one-eighth to one-tenth its volume of concentrated hydrochloric acid. Take a small piece of copper wire cleaned bright with sandpaper, roll it up so that it can be dropped into the test solution, then boil for 15 minutes. If arsenic is present, the copper wire is turned black or brown. If the wire remains bright there is no arsenic in the solution.

2. Another test is as follows:

Pass sulphuretted hydrogen (H_2S) through a warm, dilute solution of electrolyte. If a yellow precipitate forms, it is probably arsenic, but may be sulphur, caused by oxidation of H_2S by ferric salts or nitrates. Take two test tubes and put a portion of the yellow liquid in each. Add to one ammonium sulphide, to the


50
45
40
a
35
d
30
xture by weight

other ammonium carbonate. If the yellow precipitate is an arsenic compound, it will be dissolved by the ammonium sulphide, but not by ammonium carbonate.

Acetic Acid.

Add ammonia to solution until it becomes neutral; then add ferric chloride (Fe_2Cl_6). If the solution turns red, and is afterward bleached by the addition of hydrochloric acid there is acetic acid present.

Organic Matter. An accurate test for organic substances can only be carried out by a trained chemist. A good rough test is to boil some of the electrolyte in a clean beaker, until the acid becomes concentrated and begins to give off white fumes. If the liquid becomes discolored, the presence of organic matter of some kind is indicated.

The foregoing tests are given in the order of their importance. If the first four tests indicate freedom from platinum, iron, chlorine and nitrates, it is reasonably safe to assume that the electrolyte is suitable for use and the others may be omitted, though it is better to make all the tests indicated. Care must be used to avoid introducing any of the impurities tested for by the use of impure water or chemicals.

Plate I shows a set of curves and co-ordinates by means of which the density of mixtures for any given percentage of acid, up to 40 %, may be determined, for any temperature between 32° and 120° Fahrenheit. Conversely, the percentage of acid in a mixture of given density and temperature may be found, as may also the change of density of any mixture with change of temperature.

1. To find the density of liquid having a given percentage of acid: Read off the percentage on the vertical scale at the left of the upper half of the sheet. Follow horizontally over to the intersection of the horizontal line with the curve representing the density of the acid entering into the mixture. From the intersection thus found, follow vertically down to the horizontal scale marked "specific gravity," where the density will be shown for a temperature of 60° F. or 15.5° C.

As an example, find the specific gravity of a mixture containing 36½% of 1.835 acid at 60° F. Starting at point *a* follow horizontally to point *b*, as indicated by the dotted line *ab*, the point *b* being the intersection of the horizontal with the curve of 1.835 acid.

From point *b* follow vertically to the base line, the vertical cutting the base line at point *c*, which gives a value of 1.269 for the density.

If the temperature of the mixture is above or below 60°, follow the vertical line down past the horizontal scale until it intersects the diagonal line on which is marked the required temperature. This gives a second intersection from which a horizontal line must be followed, toward the left, until it crosses the vertical scale on which densities are marked. The intersection of this horizontal with the vertical scale shows the density of the mixture for the given percentage of acid and temperature.

Example.

What is specific gravity of mixture containing 32% of 1.835 acid at 90° F.? Ans. 1.224.

This is found by starting at point *d*, on line of percentage, and following horizontally to the curve of 1.835 acid, the intersection being at point *e*. From *e*, go vertically down, past the base line to the diagonal on which is marked the temperature 90°. The intersection of the vertical with this diagonal is at point *f*. Thence horizontally to the lower vertical line of specific gravities on the left, the point *g* is found which shows the gravity to be 1.224.

It is here to be noted that commercial acid is 1.835 specific gravity, and this should be the curve used for practical mixing. H_2SO_4, however, is 1.842 specific gravity, and this curve should be always used to determine percentages and densities for electrochemical calculations.

2. To find percentages of acid in solutions of given density and temperature:

Read the given density on the one of the lower vertical scales on which this density is found. Follow horizontally to the right until the horizontal intersects the diagonal line of the given temperature. Take a vertical from this point upwards until the curve is intersected. Follow a horizontal from the last intersection, over to upper vertical scale on the left. The point thus located gives the percentage of acid (1.835 or 1.842 according to the curve used) required to produce the given density at the specified temperature.

This operation is simply the converse of the preceding one.

3. To find change of density with change of temperature:

Locate given density on one of the lower vertical scales. Follow horizontally to intersection with diagonal line of given temperature. From this intersection follow vertically up or down (accord-

ing to whether the temperature at which the density is to be found is higher or lower than observed temperature) to the intersection of vertical with the diagonal line of temperature at which the density is required. From the intersection thus found, follow back horizontally towards the left to scale on which the first reading was taken. The point located by the intersection of the last horizontal and the vertical scale will show the density at the changed temperature.

As an example, what is the density of an electrolyte at 40° which shows a specific gravity of 1.250 at 100°? Starting at point *h* on left-hand lower vertical, corresponding to 1.250 specific gravity, go horizontally to the right until diagonal of 100° is reached at point *k*. Move vertically — in this case downward — until the diagonal of 40° is intersected at *m*. Thence go horizontally back to the vertical on which is marked specific gravities and the point *n* is located, which shows a density of 1.267.

When temperature values other than those given by the diagonals are required, imaginary lines must be interpolated at some distance between the two diagonals having the next values above and below the required temperature. Thus 85° would require a line, or points of intersection, to be located halfway between the 80° and 90° diagonals.

Sulphuric acid tables giving weights, percentages, and specific gravities of varying mixtures of sulphuric acid and water are given at the end of this chapter.

It has been found, experimentally, that when nitric acid is present in a cell and accompanied by metallic impurities, the electrolyte becomes much warmer on charge than the normal heat rise, and instances have been known where this increase in temperature has been so great as to crack glass containing jars.

This abnormal temperature increase is obviously due to certain secondary chemical reactions which take place in the cell.

Excessive heating therefore indicates either a high internal resistance due to sulphate or impurities in the electrolyte. It must not be assumed, however, that all impurities will cause a noticeable rise of temperature.

The quantity of electrolyte necessary for a given cell depends on its ampere-hour discharge, the initial density of the electrolyte, and the terminal density at the end of discharge. This is computed as follows:

From the fundamental equation,

$$Pb + PbO_2 + 2\,H_2SO_4 = 2\,PbSO_4 + 2\,H_2O,$$

it is obvious that for each unit of current which is discharged, two electro-chemical equivalents of H_2SO_4 must be decomposed, and since the ampere hour equivalent of H_2SO_4 is 1.826 grams, twice this, or 3.652 grams (= 0.129 oz. avoir.), are decomposed for each ampere hour of discharge. The molecular weight of H_2SO_4 is 98, while that of water is 18, and assuming that H_2SO_4 is made up of $SO_3 + H_2O$, the proportion of water in H_2SO_4 is 18/98 = 0.1837. Therefore in one ounce of H_2SO_4 there is 0.1837 oz. of water.

For each ampere hour of battery discharge, there is decomposed 0.129 oz. of H_2SO_4, of which 0.8163 parts are SO_3; that is, 0.129 × 0.8163 = 0.1053 oz. of SO_3 are abstracted from the electrolyte for each ampere hour of battery discharge, leaving behind the original water of dilution in the electrolyte and also that released from the H_2SO_4, which latter amount is 0.129 − 0.1053 = 0.0237 oz. From these data, the change in electrolyte density can easily be computed.

The author has devised a simple formula for calculating the quantity of electrolyte required, which is as follows:

Let S = ampere hours discharge;
" x = quantity of electrolyte required, in ounces avoir.;
" D = per cent. of H_2SO_4 in electrolyte at beginning of discharge;
" d = per cent. of H_2SO_4 in electrolyte at end of discharge;

Then Dx = weight of H_2SO_4 in electrolyte at beginning of discharge, and x − Dx = weight of water in electrolyte.

At end of discharge, the amount of water in electrolyte is
$x - Dx + 0.0237\,S$ (24)

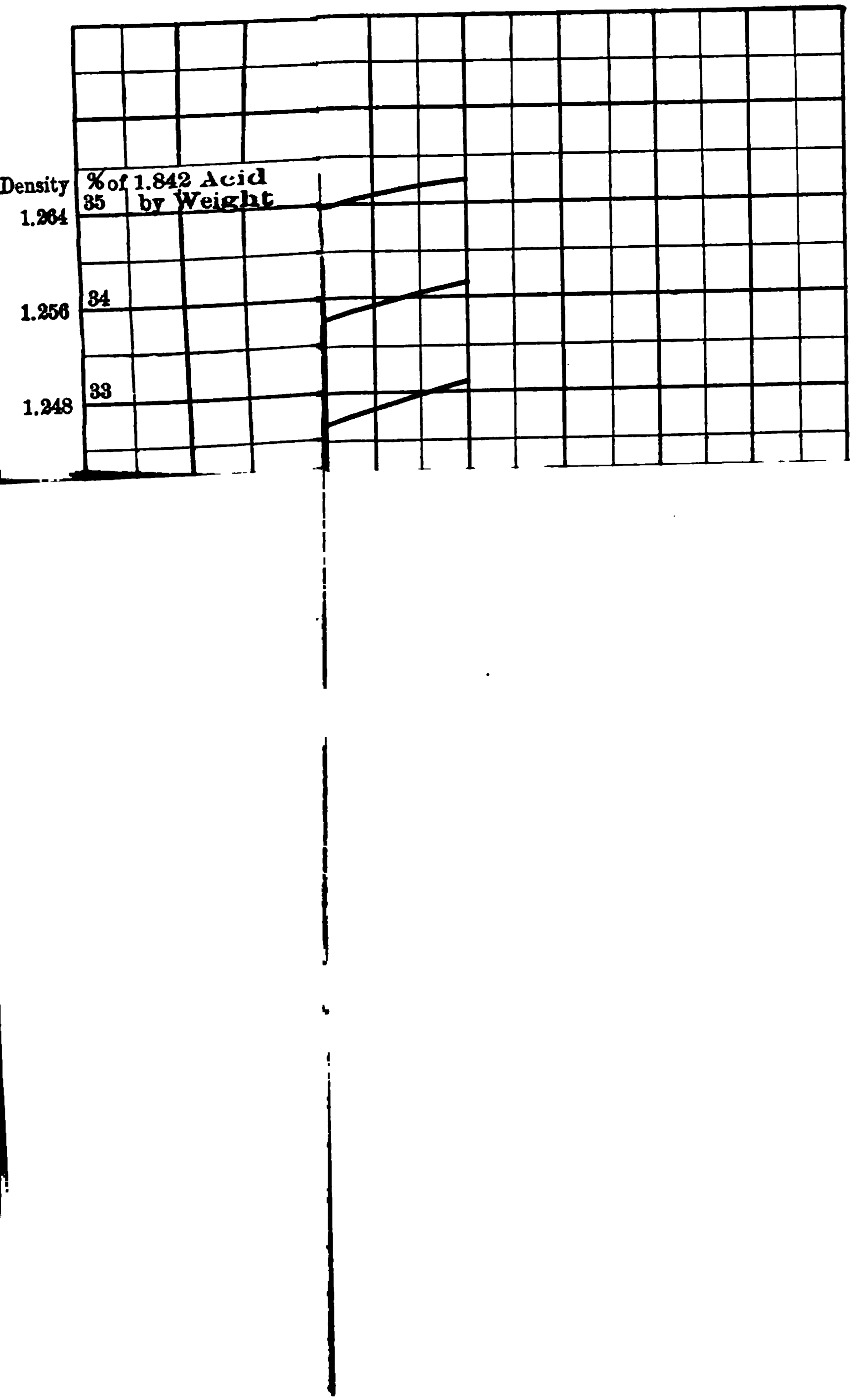
The amount of electrolyte remaining is $x - 0.1053\,S$ (25)
and the amount of H_2SO_4 is $d\,(x - 0.1053\,S)$ (26)

Also from (25) and (26), the weight of water in the electrolyte at end of discharge is

$$(x - 0.1053\,S) - d\,(x - 0.1053\,S). \quad (27)$$

Equating (24) and (27) and solving,

$$x = \frac{S\,(0.129 - 0.10.53\,d)}{D - d}. \quad (28)$$



Density
% of 1.842 Acid by Weight
35
1.264
34
1.256
33
1.248

Taking S as 100 ampere hours, (28) becomes

$$x = \frac{12.9 - 10.53\,d}{D - d}. \qquad (29)$$

If D and d are to be taken as whole numbers and not as decimal quantities, (29) becomes

$$x = \frac{1290 - 10.53\,d}{D - d}. \qquad (30)$$

For any discharge other than 100 ampere hours, the product of the actual discharge and the value of x as computed, divided by 100, will give the desired quantity of electrolyte.

In Plate II is shown a series of curves designed by the author for the use of a battery manufacturing company, and which give the relations between the ampere hours discharge; the initial density of electrolyte when battery is fully charged; the terminal density of electrolyte at any period of discharge, and the quantity of electrolyte in the cell.

Call Ampere Hours................................"A.H."
" Initial Density....................................." I "
" Terminal..."T"
" Quantity.."Q"

The curves are calculated to show I, T and Q for 100 ampere hours, electrolyte at 60° F. Other discharges may be referred to the curves by proper corrections for temperature and discharge.

The vertical, left-hand scale shows percentages of acid of density 1.842 in the mixture, and the density corresponding thereto at 60° F. The lower horizontal scale shows the quantity of electrolyte in ounces avoirdupois.

The separate curves are each for a given *initial* density and percentage of electrolyte.

1. To find quantity of electrolyte required (Q) when A.H., I, and T are given:

If A.H. = 100 and temperature = 60° F., follow horizontal corresponding to desired terminal density from vertical scale on left to curve of given I. From this intersection follow, vertically, downward to lower scale where Q is read off.

If temperature is other than 60°, refer to Plate I and find the equivalent density at 60° by method previously given, and use the corrected densities thus found as I, and T.

If A.H. is some discharge other than 100 ampere hours, the actual quantity $= \frac{Q \times A.H.}{100}$ in which Q = reading on lower horizontal scale.

2. If A.H., I and Q are given, to find T:

If A.H. = 100 and temperature = 60°, follow vertical from lower scale at point of given Q, to curve of given I. From intersection thus found, follow horizontally to left and read on vertical scale the value of T.

If temperature is not 60°, correct I for temperature as above explained, using the corrected value of I for locating curve. *After finding* T, correct this also for temperature.

If A.H. is some value other than 100, correct by formula $\frac{100\,Q}{A.H.} = QC$. Use this value QC as the starting point on the horizontal scale instead of Q, and proceed as before.

3. Given A.H., Q and T to find I:

Take a vertical up from Q and a horizontal across from T. Their intersection will fall on a curve of I, which will show the I sought, if A.H. = 100 ampere hours. If the intersection falls between two curves of I, the value of the I sought must be estimated by its position with reference to the two curves between which it falls.

The before mentioned temperature corrections must be applied to T before beginning, and to I after obtaining the result.

If the A.H. is some value other than 100, Q must be corrected, and the value $QC = \frac{100\,Q}{A.H.}$ used as the starting point on the horizontal scale.

4. If Q, T and I be given, it is possible to determine the number of ampere hours taken out of a battery, provided proper temperature corrections of T and I be made; making these corrections and using the corrected values:

Follow a horizontal from T to I. From intersection of the horizontal with I, to follow a vertical down to a horizontal scale. Take the reading on this scale, at the intersection of the vertical, and call this g.

Then $$A.H. = \frac{Q \times 100}{g}.$$

Examples.

1. In a cell which is to give 100 ampere hours, how many ounces of electrolyte are required, if the density on beginning of discharge be 1.250 and the terminal density is to be 1.195, densities being taken at temperature at 60° F.? Ans. 145 oz.

2. If cell is to give 80 ampere hours on discharge, and the density is 1.265 before the beginning charge at temperature of 100° F., and a density of 1.185 be required at end of discharge, temperature being 70° F., how many ounces of electrolyte are required? Ans. 77.6 oz.

This problem is solved as follows: From Plate I the initial and terminal densities are corrected for temperatures, both being reduced to their equivalent at 60° F. The corrected temperatures are : 1.265 at 100° becomes 1.276 at 60°; 1.185 at 70° becomes 1.189 at 60°. Taking these at initial and terminal densities respectively, the weight of electrolyte for 100 ampere hours is found from the curve which is 97 oz. For 80 ampere hours the amount is $\frac{97 \times 80}{100} = 77.6$ oz. It is to be noted that the value of the initial density — 1.276 — has no curve. Therefore, a point on the horizontal line from the reading 1.189 on the left-hand scale must be chosen between the curves 1.270 and 1.280, about .6 the distance from 1.270 towards 1.280. This can be divided by the eye closely enough for all practical purposes.

In succeeding problems the temperature of the mixture will be taken as 60°; it being understood that all densities must be properly corrected to this temperature if they differ from it.

3. Initial density 1.225, terminal 1.176, ampere hours discharge 210. What is the weight of electrolyte in the battery? Ans. 363 oz. The reading of 173 oz. is for 100 ampere hours, the quantity is $\frac{173 \times 210}{100} = 363.3$ oz.

4. A cell contains 238 oz. of electrolyte of density 1.240 at beginning of discharge. Later the density becomes 1.200. How many ampere hours have been taken out of the battery? Ans. 116 ampere hours. In this the curve shows that 205 oz. are required to deliver 100 ampere hours; therefore the discharge due to 238 oz. would be $\frac{238}{205} \times 100 = 116$ A.H.

5. A cell containing 240 oz. of electrolyte discharges 162 ampere hours, and the final density of electrolyte is 1.147. What was the density of beginning on discharge? Ans. 1.208. 240 oz. of electrolyte and 162 ampere hours gives $\frac{240 \times 100}{162} = 148.2$ oz. for 100 ampere hours. The intersection of the vertical from 148.2 and the horizontal from 1.147, falls between the curves 1.200 and 1.210, near the latter. Dividing visually, the value is seen to be about 1.208.

6. A cell contains 113 oz. of electrolyte, density 1.245. What will be the density when 106 ampere hours are discharged? Ans. 1.164. $\frac{113 \times 100}{106} = 106.5$ which is the number of oz. per 100 ampere hours. Starting from 106.5 oz. and going up to a point about midway between the curves 1.240 and 1.250, the position of the horizontal line over to the vertical scale is located, and the value of the terminal density given.

After a little practice, the use of these curves will be found very simple, and nearly any problem in battery work, relating to electrolyte densities, and their changes with current input or output, can be solved by mere inspection.

In practice, the variation in density of electrolyte with ampere hours discharged does not appear to conform to the theoretical unless the discharge rate is very low.

Numerous experiments made in this country and abroad, particularly in Germany, seemed to indicate that the higher the rate of discharge the less is the abstraction of S and O, and the smaller the diminution in density. Also, with a given rate of discharge, the change in density is less toward the end of discharge than in the beginning.

In 1902, it occurred to the author that an explanation of the divergence of fact and theory could be found in the retarded diffusion of the electrolyte, when the surface layer of active material has become partially sulphated and thereby closed the pores in the surface of the plate.

This condition prevents that portion of the electrolyte absorbed and contained within the pores of the active material from diffusing and mixing with the free electrolyte in the cell, nor can the free electrolyte pass into the pores of the plate and come in contact with the unused portion of the active material. As further dis-

charge takes place, the only SO_3 available for the necessary chemical combination is that in the electrolyte contained within the pores of the active material, and this quantity is, of course, comparatively small. The final result is the extreme dilution of the electrolyte within the pores of the plate, while the external electrolyte is changed but little. When discharge is rapid, the surface of the plates very soon passes into the form of lead sulphate, and the increase in its volume closes up the outer pores, masking the active material and imprisoning some electrolyte within the pores of the plate, while the main body of the electrolyte in the cell is excluded from the unsulphated active material. The same condition exists when the plate has been discharged for some time at moderate rates.

From these premises, the natural conclusion is that at the end of discharge there exist two separate bodies of electrolyte; one contained in the pores of the plates, greatly diluted — almost to the point of pure water — while outside the surface of the plates there is another body which has suffered comparatively little change. If these two bodies could diffuse and mix thoroughly, the density of the resulting mixture should be the same for a discharge of a given number of ampere hour, regardless of the rate at which this discharge took place.

Some experiments were made to determine the correctness of this theory, which consisted in discharging a given cell at various rates and then allowing it to stand discharged for several hours. The density of the electrolyte would gradually fall, and, in every instance, approached nearly to the calculated value. The time of standing required to attain a constant value for the electrolyte density was less with a cell made up of Planté plates, having a thin layer of active material, than with a pasted plate having a thick layer, just as would have been expected. From the results of these experiments, the writer feels justified in affirming that the amount of SO_3 abstracted for a given ampere hour discharge is constant and independent either of rate of discharge or the amount of charge in the cell at the beginning of discharge. This shows the dependence of the chemical action on the electrolyte imprisoned in the pores of the active material, in rapid and prolonged discharge.

It is to be understood that all the foregoing computations are therefore simply averages of the electrolyte densities outside and

inside the pores of the plate. They do not indicate the degree of dilution of the acid in the pores, which is far greater than that measured in the external mass of electrolyte.

The question of change in capacity with increase in quantity of electrolyte has been investigated at length by H. Wehrlin * and the accompanying curves (Fig. 7) show the increase produced by the addition of electrolyte, these being plotted from readings made on actual experiments. The decrease of acid density as the discharge goes on is also shown.

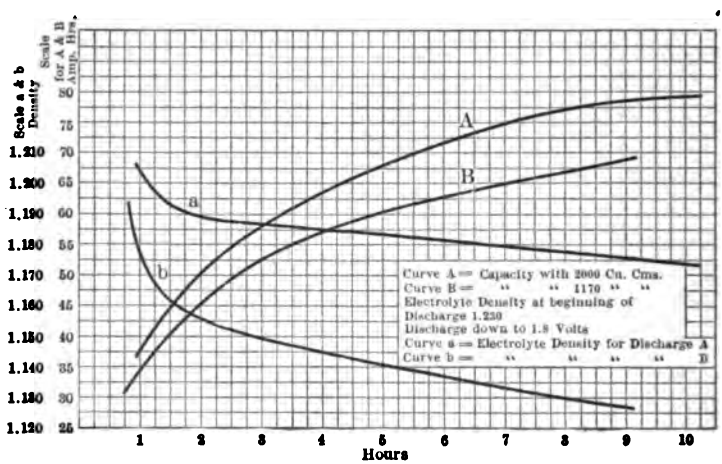


FIG. 7. Variation in Capacity with Quantity of Electrolyte.

A good general rule is to use low concentration — not above 1.210 — and provide enough acid to keep the terminal density well up — say to 1.180 to 1.190. Use the electro-chemical formula for the maximum and provide fully the quantity of electrolyte calculated.

While low density electrolyte is advantageous, if too dilute, abnormal sulphation is produced.

The more electrolyte there is present, the better the performance of any given cell.

The general practice in this country in regard to initial and terminal densities, quantity of electrolyte per 100 ampere hours, is as given in the table below:

* Centralblatt für Accumulatoren, No. 4, 1901.

TABLE VIII. — ELECTROLYTE IN STORAGE CELLS.

INITIAL AND TERMINAL DENSITIES AND QUANTITY. AVERAGES IN UNITED STATES PRACTICE.

Kind of Plates.	Character of Service.	Discharge Rate.	Densities.		Lbs. Electrolyte per 100 amp. hrs.
			Initial.	Terminal.	
Pasted pos. and and neg.	Motor car propulsion.	4 hours	1.300	1.100	4 lbs.
Planté, pos. pasted neg.	General use — Small sizes	8 "	1.210	1.187	22 lbs.
Planté, pos. pasted neg.	General use — Large sizes	1 " 8 "	1.210	1.777	15 lbs.
Planté, pos. and neg.	General use — Small sizes	8 "	1.200	1.180	25 lbs.
Planté pos. and neg.	General use — Large sizes	1 " 8 "	1.200	1.165	15 lbs.

These are only *averages* of general practice. Many storage cells vary appreciably from these data, but the figures given represent good practice.

The reader may think it strange that in this discussion no use has been made of the term "degrees Beaume." The reason is that the author considers it utterly useless, and, in fact, an absurdity to make use of a system which means nothing, and which must be converted into specific gravity in order that it should have any meaning. The system has no place either in theory or practice, and the only rational system is the direct use of specific gravity values.

Following are tables giving the constants of electrolytes of various densities at 60° F.

TABLE IX.

SULPHURIC ACIDS. — MIXTURE BY WEIGHT.

Sp. gr.	Wt. in lbs. per cubic foot.	Per cent of 1.835 acid.	Lbs. of 1.835 acid in 1 cu. ft.	Per cent of 1.842 acid.
1.000	62.37	0.00	0.00	0.000
1.007	62.81	1.00	0.63	0.935
1.014	63.24	2.50	1.58	2.337
1.021	63.68	3.66	2.33	3.422
1.028	64.12	5.00	3.21	4.675
1.036	64.62	6.00	3.88	5.610
1.043	65.05	7.00	4.55	6.545
1.051	65.55	8.00	5.24	7.480

SULPHURIC ACIDS — Continued.

Sp. gr.	Wt. in lbs. per cubic foot.	Per cent of 1.835 acid.	Lbs. of 1.835 acid in 1 cu. ft.	Per cent of 1.842 acid.
1.058	65.99	9.00	5.94	8.415
1.066	66.49	10.25	6.82	9.584
1.074	66.99	11.50	7.70	10.752
1.082	67.48	12.50	8.44	11.637
1.090	67.98	13.60	9.25	12.716
1.098	68.48	14.70	10.07	13.744
1.107	69.04	16.00	11.05	14.960
1.115	69.54	17.00	11.82	15.895
1.124	70.10	18.25	12.79	17.064
1.133	70.67	19.60	13.85	18.326
1.144	71.23	21.00	14.96	19.635
1.151	71.79	22.00	15.79	20.570
1.160	72.35	23.25	16.82	21.739
1.169	72.91	24.50	17.86	22.907
1.179	73.53	26.00	19.12	24.310
1.188	74.10	27.25	20.19	25.479
1.198	74.72	28.50	21.30	26.647
1.208	75.34	30.00	22.60	28.050
1.218	75.97	31.25	23.74	29.219
1.229	76.65	32.75	25.10	30.621
1.239	77.28	34.00	26.28	31.790
1.250	77.96	35.50	27.68	33.192
1.261	78.65	37.00	29.10	34.595
1.272	79.33	38.37	30.44	35.876
1.283	80.02	39.75	31.81	37.166
1.295	80.77	41.25	33.32	38.569
1.306	81.46	42.62	34.72	39.850
1.318	82.20	44.00	36.17	41.140
1.330	82.95	45.50	37.74	42.542
1.342	83.70	47.00	39.34	43.945
1.355	84.51	48.50	40.99	45.347
1.368	85.32	50.00	42.66	46.750
1.381	86.13	51.50	44.36	48.152
1.394	86.94	53.00	46.08	49.555
1.408	87.82	54.50	47.86	50.957
1.421	88.63	56.00	49.63	52.360
1.436	89.56	57.50	51.50	53.762
1.450	90.44	59.00	53.36	55.165
1.465	91.37	60.50	55.28	56.567
1.479	92.25	62.00	57.20	57.970
1.495	93.24	63.50	59.21	59.372
1.510	94.18	65.00	61.22	60.775
1.526	95.18	66.50	63.29	62.177
1.542	96.17	68.00	65.40	63.580
1.559	97.23	69.70	67.77	65.169
1.576	98.30	71.30	70.09	66.665
1.593	99.36	73.00	72.53	68.255
1.611	100.48	74.60	74.96	69.751
1.629	101.60	76.20	77.42	71.247
1.648	102.79	77.87	80.04	72.808
1.666	103.91	79.50	82.61	74.332
1.686	105.16	81.30	85.50	76.015
1.706	106.40	83.00	88.31	77.605

SULPHURIC ACIDS — Continued.

Sp. gr.	Wt. in lbs. per cubic foot.	Per cent of 1.835 acid.	Lbs. of 1.835 acid in 1 cu. ft.	Per cent of 1.842 acid.
1.726	107.65	85.00	91.50	79.475
1.747	108.96	87.00	94.80	81.345
1.768	110.27	89.00	98.14	83.215
1.790	111.64	91.62	102.29	85.665
1.801	112.33	93.12	104.60	87.067
1.807	112.70	94.00	105.94	87.890
1.812	113.01	94.70	107.02	88.544
1.818	113.39	95.66	108.47	89.442
1.824	113.76	96.80	110.12	90.508
1.830	114.14	98.33	112.23	91.939
1.835	114.45	100.00	114.45	93.500

TABLE X.

APPROXIMATE BOILING POINTS.

Acid density.	Deg. F.	Acid density.	Deg. F.
1.526	291	1.768	423
1.706	378	1.790	446
1.726	388	1.812	475
1.747	403	1.835	522

CHAPTER VII.

ELECTRO-MOTIVE FORCE AND ITS VARIATION.

THE open circuit electro-motive force of a storage cell is dependent on:

(1) Density of the electrolyte.

(2) Temperature.

(3) Character of active material.

The potential difference at the terminals of a cell is dependent on these factors, and also on:

(4) Rate of Current Flow.

(5) State of Charge of the cell.

(6) Internal Resistance.

The changes in electro-motive force due to variation of acid density have been pointed out, generally, in Chapter IV. The analysis and the equations show that the electro-motive force increases with increase in concentration. This dependence was early shown by Preece,* Heim,† Duncan,‡ Streintz,§ Gladstone and Hibbert,‖ and others.

The electro-motive force at various electrolyte densities may be calculated by the following formula, due to Streintz:

$$E = 1.850 + 0.917 (S - s); \qquad (31)$$

E = Electromotive force in volts;

S = Specific gravity of electrolyte;

s = Specific gravity of water;

the two specific gravities being taken at the temperature of observation.

This formula may also be written:

$$E = 1.850 + 0.00057 z, \qquad (32)$$

where z = grams of H_2SO_4 per liter of electrolyte.

* Proceedings of the Royal Society, 1883.

† Elektrotechnische Zeitschrift, Vol. X, page 88, 1889.

‡ Transactions A. I. E. E., 1889.

§ Wiedemann Annalen, Vol. XLVI, 1892, page 449.

‖ Proceedings Institution of Electrical Engineers, 1892.

These formulæ do not hold for the extremes of concentration — zero or 100% — but are correct for densities of from 1.050 to 1.650.

Figure 8 shows the curve of voltage variation between pure sponge lead and lead peroxide electrodes on open circuit with varying degrees of acid concentration. From specific gravities of 1.050 to 1.300, the increase is uniform and indicated by the

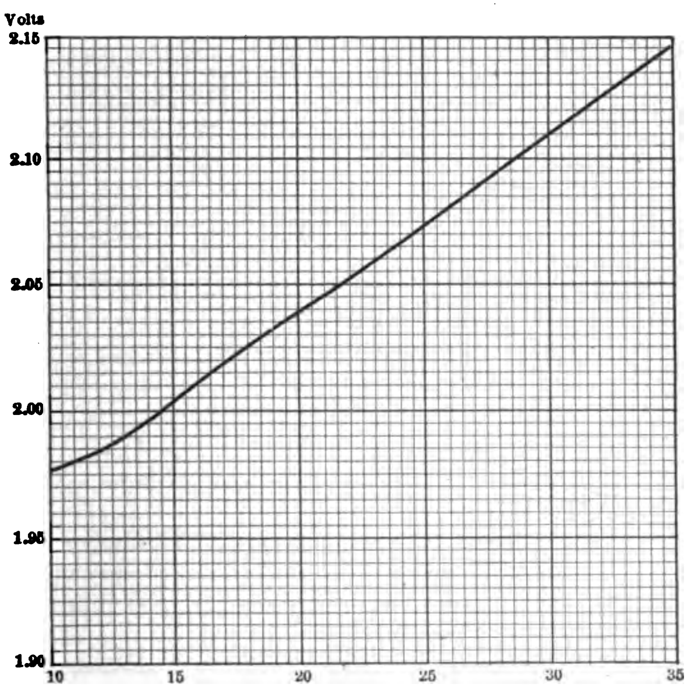


FIG. 8. Variation of Cell Potential with Electrolyte Density.

straight portion of the curve. Below and above these values, the rate of change in electro-motive force is variable, for with weaker acid, the nature of the reactions undergoes a fundamental change, while with stronger acids, local action between the sponge-lead plate and the acid begins to take place, and this prevents the electro-motive force from rising at the same rate as it does with lower concentrations.

Gladstone and Hibbert conducted a series of tests on the poten-

tial of the individual electrodes and obtained the results shown in Fig. 9. Curve 1 is the variation in electro-motive force of the positive (PbO_2) plate, while curve 2 is the variation on the negative (Pb) electrode. The dotted line is the sum of these two, which shows the increase with the change in acid concentration.

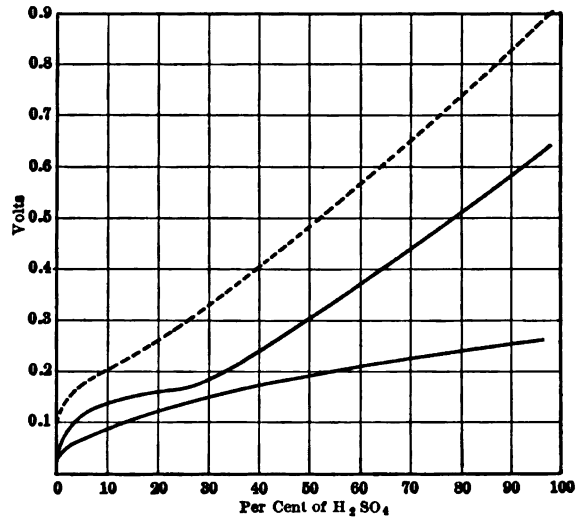


FIG. 9. Variation of Potential of Individual Electrodes with Electrolyte Density.

The electrode potential increases slightly with temperature by the amount $T \frac{\partial E}{dT}$, or the temperature coefficient, which has been discussed in Chapter IV.

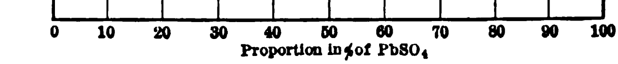


FIG. 10. Variation of Positive Electrode Potential with Proportion of $PbSO_4$.

With different states of charge and discharge there is a variation in electro-motive force, due to the mixture of sulphate with

the active material. Darrieus has measured these variations and the results of these measurements are given in the accompanying curve, Fig. 10, which shows the changes in electro-motive force for PbO_2 mixed with varying proportions of $PbSO_4$, the measurements being made against a pure sponge lead negative in acid of 1.320 specific gravity. This curve, in its gradual diminution and abrupt fall near the end, resembles, somewhat, the voltage curve of the cell.

When charge or discharge currents flow into or out from the cell, the potential difference, or terminal voltage, changes greatly with the time during which current flow through the cell continues and with the rate of flow, as has been mentioned in a previous chapter.

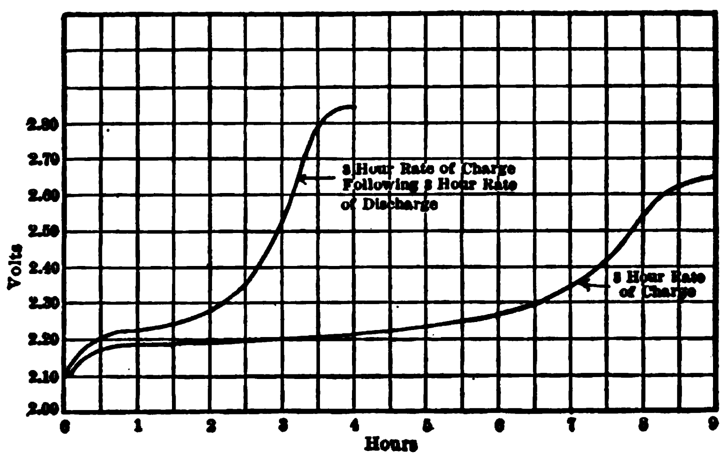


FIG. 11. Curves of Charge at Different Rates.

Figure 11 shows two voltage curves for different rates of charge of a certain cell having Planté plates. An analysis of these curves shows that the normal open circuit voltage of a lead cell having an electrolyte density of 1.210 is about 2.10 volts. On charge, as soon as current flow begins, the terminal voltage quickly rises until it reaches a value of about 2.18 for the normal charge rate, after which it continues to rise very slowly until it attains a value of about 2.25 volts; it then ascends rapidly until the maximum of 2.5 to 2.7 volts — depending upon the character of the plates — is reached. The rapid increase at the beginning of charge, as shown by the first part of the curve, is caused principally by

a polarization counter electro-motive force, while the gradual increase of voltage extending over a long period is due to the increase in density of the electrolyte contained within the pores of the plates. Since these concentration changes take place in the interior of the active material, they are far greater than the variations in the density of that portion of the electrolyte exterior to and surrounding the plates.

The last portion of the curve of charge, which is marked by the rapid upward rise, begins when the sulphate on the electrodes has all been reduced and the products of the electrolysis are hydrogen and oxygen. Since lead cannot occlude hydrogen, it forms bubbles on the surface of the sponge-lead plates, which set up an electro-motive force that opposes the flow of charging current, producing the high voltage always observed at the end of charge.

Investigations made on the changes in electrode potential show that when a voltage of 2.3 has been reached on charge, the potential of the two electrodes increases very slightly, no matter how prolonged the charge may be; the increase in electro-motive force above this value being due to the evolution of gases.

It will be noted that the general form of the curve is the same, whatever the rate of charge, except that the time period of each of the effects before noted is diminished with increase in rate.

With certain types of Planté plates the curve of charge takes a slightly different shape, and shows the curious effect of a fall in voltage along a portion of the curve extending over a slight period of time.

No definite cause has been assigned for this phenomenon, but it is believed that it results from the reduction of the surface layer of sulphate which covers the active material, and when this is reduced, the internal resistance of the cell is so far diminished that its potential falls. On discharge the effects are, substantially, the opposite of those on charge.

Figure 12 shows a number of curves of discharge, which indicate the voltage and duration of the discharge at various rates.

From these it may be seen that when discharge takes place at a slow rate (curve 1) there is a sudden fall in voltage, which is followed by a gradual diminution until the capacity of the cell is practically exhausted, after which the voltage drop becomes very rapid.

At high rates, the instantaneous drop, due to polarization, is so great as to obliterate the initial rapid fall which takes place at

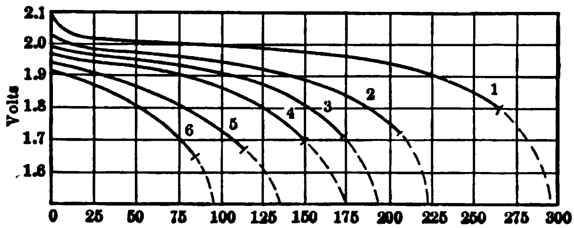


FIG. 12. Curves of Discharge at Various Rates.

the low and moderate discharge rates, and the discharge begins at less than 2 volts.

The drop in voltage, while rapid, is less at the beginning and greater near the end of discharge just as in the case of slow discharge, the general form of the discharge curves having a similarity, regardless of the rate of discharge.

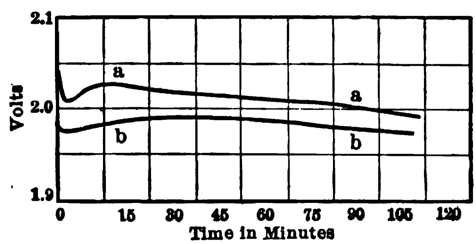


FIG. 14. Curves of Discharge, showing Initial Rise of Potential.

Sometimes, when cells having Planté plates are discharged at high rates, the discharge being begun within a short time after end of charge, there is a sudden initial drop of voltage which takes place in a very few minutes, after which the potential actually rises for a period that may extend over half the time of discharge before the normal steady decrease begins to take place. Fig. 14 shows two curves of discharge observed by Wade which exhibit these characteristics. Curve *a* is for a cell containing electrolyte of 1.220 specific gravity, while curve *b* is for one containing 1.190 acid. Causes other than the mere difference in acid density probably produced the difference in form of these two curves. The reasons for these voltage rises are not known.

It is to be noted that the area included between the charge and discharge curves represents lost energy, and the separation of these curves is greater at higher rates of charge and discharge than with low rates, which shows the effect of the charge and discharge rates on the efficiency of the cell. The differences between the charge and discharge curves are partly due to polarization and ohmic drop, but the principal cause lies in changes in acid concentration, the acid in the pores of the plates becoming denser with charge, and more dilute with discharge. This is proven by the fact that the curves tend to approach each other more and more as the rates of charge and discharge are lowered, and by a greater amount than the voltage changes due to polarization and resistance would account for. At low rates the diffusion of electrolyte may more nearly keep pace with the rate of change in the concentration.

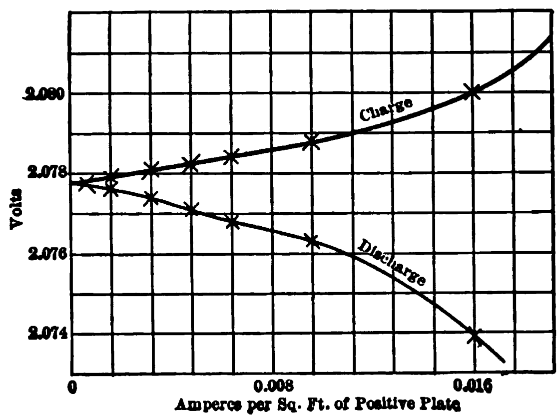


FIG. 15. Difference between Charge and Discharge Potentials at Various Rates.

Figure 15 shows the variation in the voltage of charge and discharge with different rates. The points on the curves are taken as equal to the voltage of the middle section of the charge and discharge curves. The abscissæ are given in amperes per square foot of positive plate. It is to be noted that the ordinates are taken to a very small scale, the total range of the figure being only 0.009 volt.

As may be seen, the difference between the charge and discharge voltages is only 0.006 volt at a rate of 0.016 amperes per square foot, which is a loss of less than 0.3%. This shows that the

voltage of charge or discharge remains nearly constant, and approximates the open circuit voltage of the cell when the rates of current flow are very low and the concentration changes take place so slowly that the diffusion may closely follow and annul them. Incidentally, these curves show that, except for the energy absorbed by diffusion the storage battery is completely reversible if the current rate be low enough.

The dependence of the electro-motive force on the circulation of the electrolyte is shown by the fact that the most porous sponge lead cannot absorb more than two-thirds its apparent volume of electrolyte, and the sponge lead electrode under its best conditions cannot absorb more than one-half its apparent volume; therefore, for the two electrodes there could never be more than three volumes of acid absorbed to two volumes of active material. Solid PbO_2 requires about six times its own bulk of 1.200 specific gravity electrolyte to produce 50% sulphation if all the SO_3 is abstracted, leaving only water behind; or it requires at least twelve times as much electrolyte of this specific gravity as the volume of PbO_2 if the remaining electrolyte is to have any reasonable density. From this it is apparent that the acid contained in the pores is totally inadequate to give complete discharge, and it shows the dependence of the electro-motive force of the electrodes on the rate of diffusion of the electrolyte into and out from the pores of the active material.

There are several causes which tend to assist diffusion, and one is the so-called concentration currents, which exist when the acid concentration varies in the pores, or when differences in concentration between the inner and outer portions of the active material become comparatively great. Obviously, differences in electro-motive force are produced at different points in the same mass of active material by these concentration differences, and local currents of electricity are thereby set up. These local currents tend to charge certain portions of the plate, increasing the density of the electrolyte contained in those portions, and to discharge other portions, decreasing the density, and where considerable differences in concentration exist, these concentration currents, which act independently of diffusion, tend to equalize the density through the mass of the active material.

Streintz has made a study of the changes in voltage of the individual electrodes with charge and discharge. His observa-

tions are shown graphically by the curves in Fig. 16. The lower curves are those of the negative electrode, while the upper curves represent the voltage changes at the peroxide electrode, the

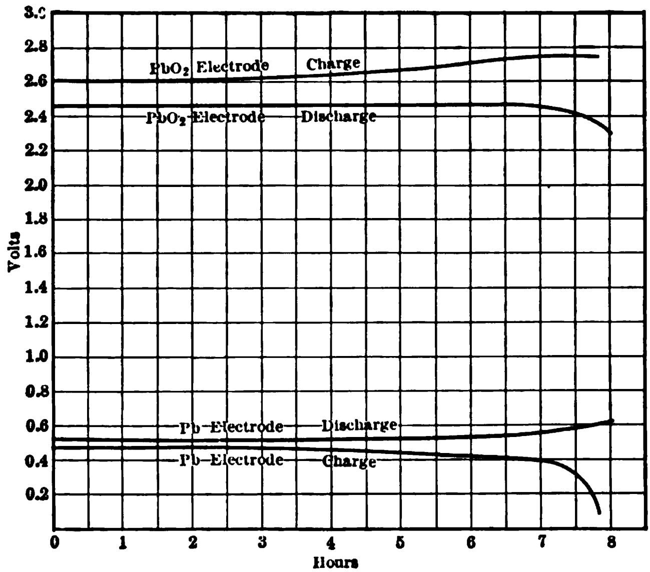


FIG. 16. Potentials of Positive and Negative Plates against Auxiliary Electrode.

readings having been made between an auxiliary test electrode of zinc and each of the two battery electrodes. The extreme upper and lower curves are those of charge, while the two inner curves show the changes on discharge. The cell potential at any time, or point on the curve, is equal to the potential of the peroxide electrode, minus that of the sponge-lead electrode. Thus, at the end of five hours of charge, the potential between the auxiliary electrode and the peroxide plate is 2.65 volts, while that between the auxiliary and the sponge-lead is 0.42 volt, both plates being positive to the auxiliary electrode. The cell potential is therefore $2.65 - 0.42 = 2.23$. The sharp, downward turn of the potential of the sponge-lead plate near the end of the charge shows that this electrode furnishes the principal opposition to the flow of charging current, and causes the high potential at this stage of charge.

From these curves it appears that the range of potential through

which the sponge-lead plate passes from charge to discharge is about 0.5 volt, while the peroxide plate range of working is about 0.4 volt. These figures include the voltage of gas liberation on charge, the effect of which is clearly shown by the drop at the end of the charge curve of the sponge-lead plate. This, however, as has been remarked, is not a true electrode potential, but is due to the auxiliary and additive electro-motive force of occluded hydrogen gas.

After having been fully charged, if the cell be given a long period of rest and then discharged, the voltage does not begin to drop off at once, but on the contrary it rises slightly. Several cycles of charge and discharge are necessary to bring the battery back to its original condition, such that the voltage at beginning of discharge is high, rapidly falling during the first few minutes.

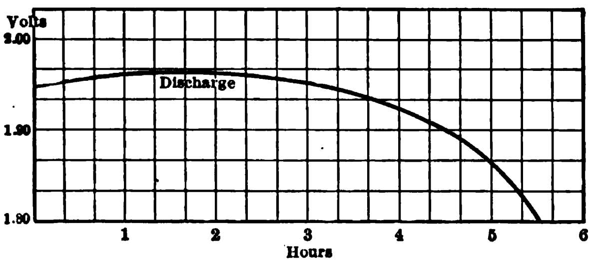


FIG. 17. Curve of Discharge after Long Rest.

Figure 17 shows the curve of discharge of a cell which has been allowed to stand idle for several days after being fully charged.

Ayrton has found that when the active material on the peroxide plate is converted into sulphate to the extent of 69% of the total, the cell loses its potential entirely. This he attributes to the formation of a surface layer of sulphate, and also to the formation of peroxide on the negative plate.

Fick has devised a mathematical law to show the rate of diffusion and the consequent rate of change of electro-motive force with concentration changes, which is as follows:

If t = time in seconds,

q = cross-sectional area of a pore in the active material in square centimeters,

l = length of pore in centimeters,

C_a = density of external acid,

C_i = density of acid inside pores,

Then, for an infinitesimal time, *dt*, an increase in the density of the acid within the pores will take place, which is equal to dC_i.

Obviously, the rate of diffusion is proportional to the cross section of the pores and the difference between the density of the external electrolyte and that contained in the pores, while it is inversely proportional to the length of the pores. Therefore,

$$dC_i = \frac{\phi(C_a - C_i)q}{l} dt, \tag{33}$$

in which ϕ is a constant.

Considering the density of the external acid, C_a, as constant, the constant quantities in the equation are C_a, ϕ, q, and l. Combining to collect the constants,

$$\frac{dC_i}{dt} = \text{const.} - \text{const } C_i. \tag{34}$$

The electro-motive force of a cell is,

$$E = 1.850 + 0.00057\, C_i,$$

whence,

$$dE = 0.00057 dC_i. \tag{35}$$

Dividing both sides of the equation by dt,

$$\frac{dE}{dt} = 0.00057 \frac{dC_i}{dt}, \text{ or } \frac{dE}{dt} = \frac{\text{const. } dC_i}{dt}.$$

Since $$\frac{dC_i}{dt} = \text{const.} - \text{const. } C_i,$$

$$\frac{dE}{dt} = \text{const. (const.} - \text{const. } C_i) = \text{const.} - \text{const. } C_i. \tag{36}$$

Also, since $0.00057C_i = E - 1.850$, and taking 0.00057 and 1.850 as constants,

$$\text{Const. } C_i = E - \text{const.} \tag{37}$$

Combining equations (36) and (37)

$$\frac{dE}{di} = \text{Const.} - \text{const. } (E - \text{const.}) = \text{const.} - \text{const. } E.$$

$$dE = a\,(b - E)\, dt,$$

in which a and b are constants.

$$\frac{dE}{b-E} = adt. \tag{38}$$

Integrating, the result is

$- \log (b - E) = at + k$, in which k is a constant of integration.

This reduces to

$$b - E = \varepsilon^{(-at-k)}.$$

$\varepsilon^{(-at-k)} = \varepsilon^{-at} \times$ a constant which is equal to ε^{-k}. Call this constant p.

Then $b-E = p \times \varepsilon^{-at}$, whence

$$E = b - \frac{p}{\varepsilon^{at}}. \tag{39}$$

If E_a = electro-motive force at density C_a and E_t = electro-motive force at density after a time of diffusion equal to t, for $t = \infty$, $E_t = E_a$, also the second term on the right of equation (39) disappears so that Const. $b = E_a$. The equation therefore finally becomes

$$E_t = E_a - \frac{p}{\varepsilon^{at}} \tag{40}$$

Also, for $t = 0$, $E_t = E_a - p$,

p being the difference between the electro-motive force before the electrolyte has time to diffuse and that due to acid having a density equal to C_a. This difference is equal to the value of the polarization electro-motive force at the end of charge.

As is well known, any storage cell which has been carried to its highest potential on charge, or its lowest voltage value on discharge, will, on opening the circuit, recover its normal voltage within a very short time, the length of time required being a constant depending upon the construction of the electrodes. This is called the "recovery of the cell." The rate of recovery has been studied by Moore.*

Figure 18 shows the curve of charge given by the full line, while the dotted line shows the rate of recovery, the abscissæ being plotted backwards for the latter curve.

Figure 19 shows a curve of discharge and the rate of recovery, the two curves being shown in full lines and dotted lines, respectively.

* Physical Review, Vol. IV, 1897, p. 353.

In this latter figure the points shown are computed from equation (39), or the diffusion law of Fick, and it will be seen that the curve found experimentally coincides very nearly with the calculated points.

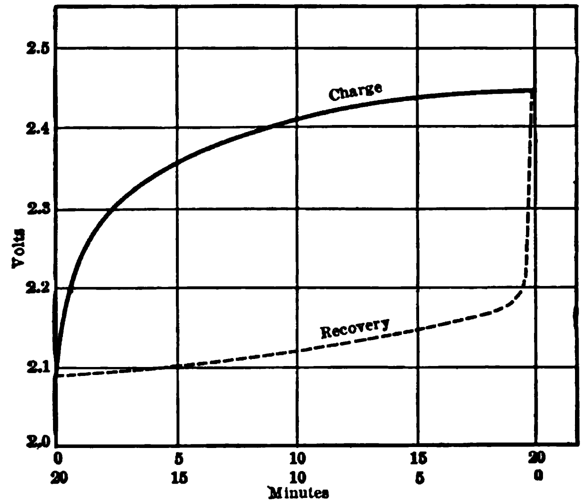


FIG. 18. Recovery of Cell Potential after Charge.

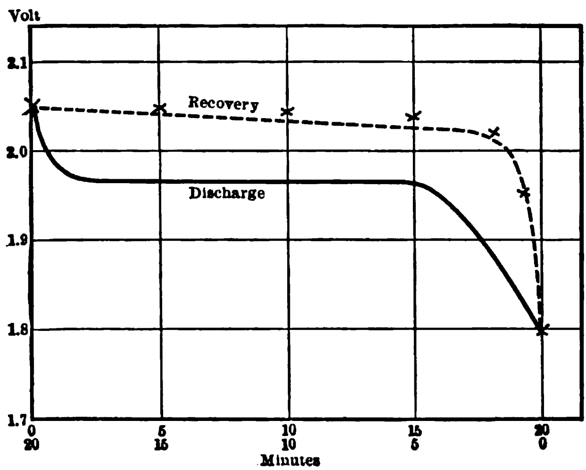


FIG. 19. Recovery of Cell Potential after Discharge.

There is another drop in electro-motive force which is different from the recovery drop and is due to the breaking up of the unstable, superoxidized compounds which are formed on charge,

such as persulphuric acid and other substances of a like character. After charge is ended, it will be observed that no hydrogen bubbles come off from the sponge lead plate after the first rush of gas, lasting only a short time, unless there be local action. The peroxide electrode, however, will give off oxygen for a considerable time, which indicates that the superoxidized bodies are breaking up, and this produces a slow decrease in electro-motive force with time. Fig. 20 shows the rate of voltage decrease for cells having

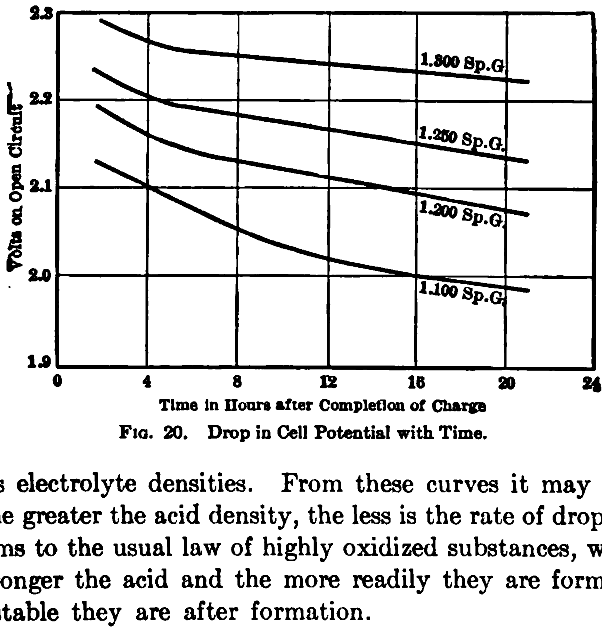


FIG. 20. Drop in Cell Potential with Time.

various electrolyte densities. From these curves it may be seen that the greater the acid density, the less is the rate of drop. This conforms to the usual law of highly oxidized substances, which is, the stronger the acid and the more readily they are formed, the more stable they are after formation.

Wade states that the final drop on discharge is not due to decrease in concentration, but to high increase in ohmic resistance, caused by a definite change in the character of the electrodes which occurs at this stage. He claims that this resistance becomes very great at a certain condition of PbO_2 + Pb + $PbSO_4$ which is reached long in advance of the plate exhaustion or complete sulphation of the active materials. Certainly the drop is not caused by loss of electro-motive force, for if the circuit be interrupted, the voltage of the cell returns to nearly its normal value; and in the case of thin plates discharged at a low rate, practically no residual discharge may be taken from the cell, which shows that this final condition does not arise from the need of acid in the

pores. With thick plates, discharged at rapid rates, there is a residual charge left of considerable magnitude, which becomes available after allowing the cell to stand on open circuit a short time, but after this residual charge is completely taken out so that any further attempt to obtain current from the cell results only in an immediate drop of voltage, it will still be found that on open circuit the cell will regain practically its normal electromotive force. From these considerations it appears that Wade's conclusion cannot be avoided and that the final drop is due to some definite change in the condition of the active material, which produces a high internal resistance.

Less energy is required to charge a battery, if it be charged immediately after discharge, than would be required if the battery be allowed to stand for some time. The reason is that the acid in the pores of the active material is very dilute, and, therefore, the counter electro-motive force is much less than it would be if time were allowed for diffusion to take place and the acid thereby attain its normal strength.

As may be seen of the curve, Fig. 10, the fall in electro-motive force on discharge, due to the character of the change of the active materials, is but slight.

The change in voltage due to internal resistance is negligible up to a certain point, after which the internal resistance becomes very great and the drop is appreciably affected by it. The curves of charge and discharge will always be of a form which shows the relation between the rate of change of acid concentration in the pores, and the rate of diffusion.

After completion of charge, when the charging circuit is open, the release of polarizing, hydrogen bubbles from the sponge lead electrodes, shows physically the loss of the element which produces the high electro-motive force of charge, and, coincidently with the release of these bubbles from the electrode surface and the diffusion which follows, the voltage of the cell falls to its open circuit value, following the curve of rate of recovery as before set forth.

Where batteries are used for regulating, that is, absorbing as charging currents the excess supplied by the generating apparatus when the external load is light, and giving out current to assist the generating apparatus when the external load is heavy, the difference in potential between charge and discharge is not so

great as the differences which exist when charge and discharge are prolonged, because the length of time which a charge or the subsequent discharge may last is very short, and therefore, though the rate may be high, the ampere-hours are small and the state of battery charge is changed but little.

Where the state of battery charge is maintained reasonably constant, the cell has a characteristic somewhat like a shunt dynamo. The voltage rises on charge and falls on discharge, the increase or decrease being directly proportional to the rate of current flow.

B. Hopkinson,* in 1901, made some extended investigations concerning the variation in voltage on charge and discharge at short intervals. He found that the difference between the charging and discharging voltages was much less than the differences which exist for prolonged periods of charge and discharge. This paper is more fully referred to in Chapter XII.

A study of the behavior of storage cells working under the condition of short charge and discharge periods, which followed each other in quick succession, was made by the author† in 1903.

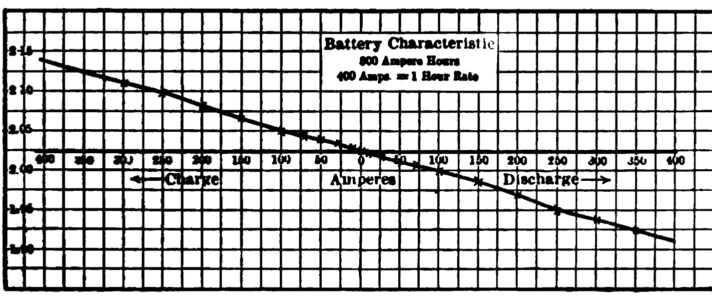


FIG. 21. Voltage Characteristic of Cell.

Figure 21 shows the characteristic of an 800-ampere-hour cell one-quarter discharged, at 70° F., and in good condition as found in this investigation. This will change with temperature, the characteristic more nearly approaching the horizontal with higher, and the perpendicular with lower, temperature. It will also change with state of charge, density of electrolyte, and condition

* London Electrician, Vol. XLVIII, pages 211, 263.

† Transactions A. I. E. E., 1903.

of plates. The ordinates above the horizontal line, which intersects the characteristic curve at zero, represent the voltage of a cell on charge, and those below this line the volts on discharge, at various rates of current flow. The abscissæ are amperes, the curve being extended on either side of the zero to that point where the current flow is equal to the one-hour rate of charge or discharge. Each reading was taken 20 seconds after beginning of the corresponding current flow. The zero point shows the voltage of a cell when current flows neither into nor out of it.

This is the general form of characteristic for nearly any type or size of cell, the conditions of charge, temperature, electrolyte, density, etc., being the same. The data, then, to construct the characteristic for any size of battery having the same constants as those given are:

Volts per cell at zero, 2.025; at the one-hour discharge rate, 1.915; at the one-hour charge rate 2.14, and connect these points by a straight line. As may be seen, that shown in the figure is practically a straight line, and repeated tests on many sizes and types of cells indicate that if the conditions be maintained constant throughout a test, and due allowance be made for the error in reading the small changes in the voltmeter deflections, the characteristic is a straight line between the points of one-hour charge and one-hour discharge rates.

The maintenance of the voltage, and consequently the capacity of the cell, depends on both the positive and negative plates and, therefore, if one be fully charged or fully reduced, and the other is only imperfectly charged, the capacity is small, being equal only to that of the least efficient plate; the battery is quickly discharged, and the voltage curve falls rapidly. It is necessary that both the positive and negative elements should be completely charged. The voltage of the battery is not always an indication of the state of charge, and in order to determine the condition of the two plates it is necessary to test them independently. This is done by immersing a piece of metal, either zinc or cadmium, in the electrolyte and observing the voltage between it and the positive and negative elements.

Zinc is now seldom used because pure zinc is difficult to obtain and when impure it dissolves in the electrolyte. If any portion be dissolved it has a tendency to deposit during charge on the negative plate, and erroneous readings would therefore result.

With reasonable care, however, there is no reason why zinc should not be satisfactory in ordinary practical work, when cadmium is not available.

Cadmium must also be free from impurities; otherwise difficulties, such as are caused by impurities in zinc, will arise. In taking cadmium readings, a substantial error will be introduced unless the voltmeter used in making the measurements has a high resistance. This is due to the polarization effect which will manifest itself if an appreciable current flow takes place between the auxiliary electrode and the plate against which it is being measured.

Before making the tests, the cadmium should be placed in the acid and allowed to stay a few minutes, so that a coating of cadmium sulphate may form before the first measurement is taken. After once being placed in the electrolyte, the cadmium should not be allowed to become dry, but should be kept wet with electrolyte until all measurements are completed. If necessary to do this, it should be moved from cell to cell immersed in dilute sulphuric acid contained in any convenient vessel. It should never be polished or scraped bright.

The cadmium must not come in contact with any of the plates or connections, and the best way to prevent this, is to cover it with rubber and perforate the covering with numerous small holes.

When a battery is discharged, that is, when the potential has fallen to 1.8 volts, the voltage between the cadmium test piece and the positive plate should be about 2.05, and between the cadmium and the negative plate 0.25, the cadmium being negative to both the elements. The voltage of the cell $= 2.05 - 0.25 = 1.8$, the cadmium negative reading being subtracted from the positive reading, when both readings are in the same direction. These readings must be made while the cell is discharging at normal rate.

When the battery is fully charged, and the normal charging current is still flowing, the voltage between the cadmium and the positive plate should be about 2.45, and the voltage between the cadmium and the negative, 0.05 to 0.10, the cadmium being positive to the sponge lead plate and negative to the peroxide plate. The cell voltage in this case is the sum of the two readings $= 2.45 + 0.10 = 2.55$.

Figures 22 and 23 show the conditions which obtain; Fig. 23 being that of discharge, and Fig. 22 being that of charge.

The positions of the respective elements indicate their relations, the right being the positive side.

At the end of discharge, the cadmium is negative to the peroxide plate, the voltage between them being about 2.05. It is also negative to the sponge lead plate, and the voltage between these two is about 0.25.

The voltage between the plates is obviously the *difference* of the cadmium readings, which is 1.8.

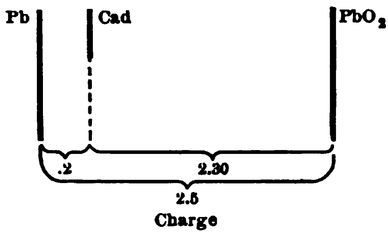


FIG. 22. Voltaic Relation between Electrodes and Cadmium after Charge.

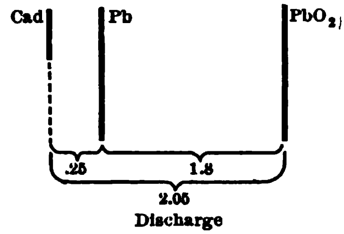


FIG. 23. Voltaic Relation between Electrodes and Cadmium after Discharge.

In Fig. 22 it is seen that at the end of charge the cadmium is still negative to the peroxide plate, and the potential difference between them has increased. The sponge lead element has changed so that the cadmium is no longer negative to it, but positive, as shown. The voltage between the cadmium and positive is 2.30; between cadmium and negative — reading in the opposite direction, however — 0.20; and the voltage between the plates is the *sum* of these two or 2.50. Therefore, it will be seen that the voltage between the battery plates is the sum of the two cadmium readings whenever the readings are in opposite directions, or when the connections to the voltmeter have to be reversed after making one reading, before the other can be made, and conversely, when both the cadmium readings are in the same direction, the voltage of the cell is equal to their difference.

In making all three readings, the sum or the difference of the two cadmium readings, as the case may be, should be equal to the observed voltage of the cell, though it is somewhat difficult in practice to measure these voltages accurately enough to make them check exactly, because of the small deflection produced between the cadmium and the negative plate.

Instances have come under the author's observation where cells on charge have shown a voltage as high as 2.5 volts and the reading between the cadmium and negative plates showed that the negative plates were still positive to the cadmium, indicating that, though the positives were fully charged, the negatives were not; and these cells showed low capacity. On continuing the charging current for some time, the negatives were finally completely reduced to lead-sponge, as shown by the cadmium readings, and the battery then showed full capacity.

No cell should be considered charged until the negative plate shows a potential of at least 0.05 volt against a cadmium electrode, and 0.10 is better, the cadmium being positive to the sponge-lead; also, the cell should be considered as discharged when the negative reaches a point where the potential between it and the auxiliary cadmium electrode is 0.25 volt, the sponge-lead electrode, in this case, being positive to the cadmium. The range, therefore, of electrode potential over the sponge-lead plate is about 0.35 volt between charge and discharge.

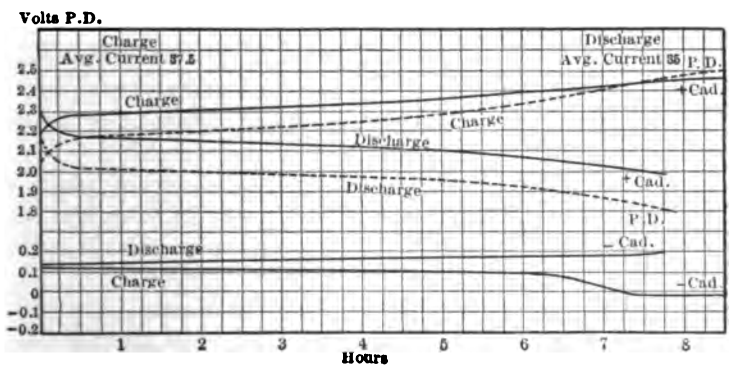


FIG. 24. Electrode Potentials against Cadmium on Charge and Discharge.

Figure 24 shows a series of curves in which the two dotted curves marked " P. D." are those of the cell voltage on charge and discharge.

The upper full-line curve marked " + cad." is the potential of the peroxide plate against a cadmium test electrode on charge, while the lowermost full-line curve, marked "– cad.," is the potential of the negative plate against the cadmium. It will be observed that near the end of charge — about the end of the sixth hour

— the potential of the negative begins to decrease rapidly and reaching zero — *i.e.*, the point where no potential exists between it and the cadmium — it sinks still further, becoming negative to the cadmium, as has been described. The curves marked "discharge + cad." and " − cad." are the voltages between the cadmium test electrode and the positive and negative plates respectively, when the cell is being discharged; the cadmium in this case being negative to both electrodes.

The copious evolution of free hydrogen and oxygen from their respective electrodes is an indication that both the plates are fully charged if the rate of charge is not higher than the six-hour rate.

For a given set of conditions, the voltage also changes with the temperature. The voltage on discharge is increased with increase in temperature, while the voltage of charge decreases with temperature increase. The reason for this lies in the accelerated diffusion of electrolyte in the pores of the plates and the decrease in the internal resistance of the cell. All electrolytes have a negative temperature coefficient, and therefore increase of temperature lowers the resistance of the cell. These effects are far greater than the change due to the temperature coefficient. The influence of temperature is discussed in Chapter XI.

It is to be noted that the form of the voltage curves may be greatly changed by the simple expedient of increasing or decreasing the relative values of the ordinates and abscissæ.

Manufacturers of cells occasionally prepare curves which are plotted from actual tests, but which appear to have but small voltage changes because the ordinates are compressed and the abscissæ lengthened.

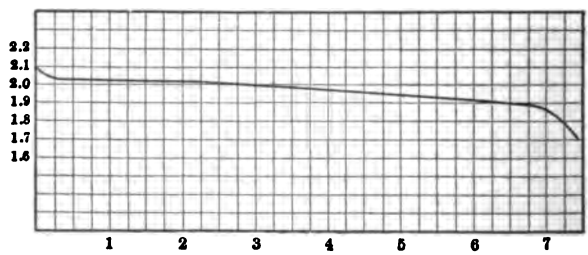


FIG. 25. Curve of Discharge to compare with Fig. 26.

Figures 25 and 26 are the same curve, the voltage values being identical for any given time; yet the cell seems to show a far better

performance in curve Fig. 25 than in Fig. 26, when merely inspected for form.

This caution is applicable to all curves which are intended to represent performance of apparatus of any kind.

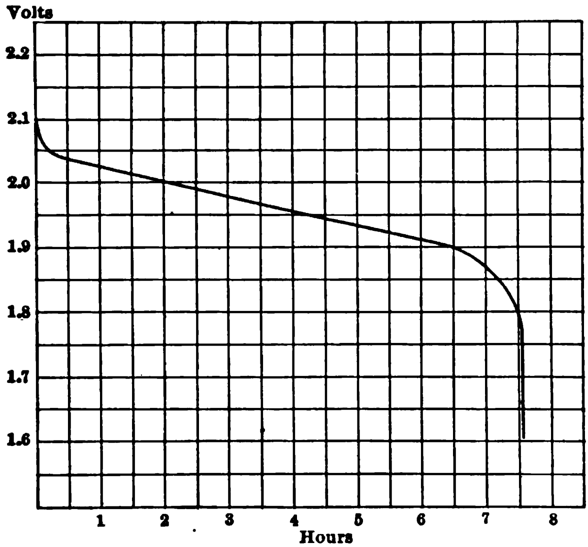


FIG. 26. Curve of Discharge to compare with Fig. 25.

CHAPTER VIII.

CAPACITY.

THE capacity of a cell is measured in ampere-hours. The energy output or watt-hours is the product obtained by multiplying the ampere-hour output by the average voltage of discharge.

In a battery made up of a number of plates, each of a definite area, and carrying a given quantity of active material, the capacity in ampere hours will vary with several factors. These are:

(1) Character of active materials,
(2) Porosity " " "
(3) Disposition " " "
(4) Quantity of electrolyte,
(5) Density " "
(6) Rate of diffusion,
(7) Temperature,
(8) Rate of discharge. ✓

The factors (1), (2) and (3) involve the matter of efficient use of active material. It is evident that with a given quantity of active material, the more porous it is made and the better it is disposed with reference to intimate contact with both the grid and electrolyte, the higher will be the capacity. Also (6), the more rapidly and thoroughly the electrolyte can penetrate to all parts of the material, the greater the discharge the battery will be capable of giving.

The effect of variation of (4) quantity of electrolyte on the capacity has already been mentioned (Chapter VI), and it has been shown that the capacity increases somewhat with the quantity.

Since the capacity of cells varies with the discharge rate, some standard rate must be taken as the basis for all capacity ratings. The arbitrary standard of the 8-hour rate is now universal, and it is on this basis that cells are manufactured and marketed. With increase in rate, the capacity is diminished, and at the 1-hour rate only about half the number of ampere-hours can be obtained from a cell that it can supply at the 8-hour rate.

The term "capacity," it is to be understood, refers to the amount of energy which may be taken out of a cell from the beginning of discharge until the gradually diminishing electro-motive force reaches some value which has been arbitrarily fixed and which is reached long before all of the active material is reduced to $PbSO_4$, and zero voltage attained.

1.80 volts is the potential which has been adopted as the stopping point of discharge when the battery is supplying current at the 8-hour rate, or 1.68 volts when supplying current at the 1-hour rate. The terminal voltage, *i.e.*, the voltage at which the battery is assumed to be completely discharged for any rate, may be computed from the formula:

$$E = 1.66 + 0.0175T,$$

in which T is the time in hours during which the discharge lasts. Thus, the final voltage for a cell at the 4-hour rate would be $1.66 + 0.0175 \times 4 = 1.75$ volts.

Discharge should never be continued after the minimum voltage as given by the above rule is reached. Further discharge will yield but few ampere-hours and at a low voltage, so that the additional energy obtainable is almost negligible. Also, excessive discharge causes abnormal expansion of the active material, thereby producing shedding, distortion — or "buckling" — of the plates, and, in extreme cases, the cracking of plate frames or grids.

For 100 ampere-hours discharged, there are required 0.844 lb. of Pb, and 0.975 lb. of PbO_2 converted into sulphate. Allowing 50% of the active material converted into sulphate, which is the maximum usually obtainable in practice, the weights are 1.688 lbs. of Pb, and 1.950 lbs. of PbO_2, making a total of 3.638 lbs. active material per 100 ampere-hours, this capacity being based on the practical discharge down to the minimum allowable voltage, as above given.

The capacity obtainable from electrodes ranges from 40 to 75 ampere-hours per square foot of positive plate (both sides included), depending on the type, density of the electrolyte, and other conditions. The capacity of Planté plates is from 40 to 60 ampere-hours per square foot of positive surface, depending on the depth of the formation and the type of plate, while pasted plates will yield from 50 to 75 ampere-hours per square foot, depending on the thickness and porosity of the active material.

Theoretically, the peroxide electrode should have a larger capacity than the sponge-lead electrode, because it is not so porous as is the sponge-lead, and therefore the concentration changes of the electrolyte in its pores are greater than in the more porous sponge-lead. In practice, however, it has been found necessary to make the sponge-lead electrodes with a much greater capacity than the peroxide electrode, the excess being sometimes as much as 100 %, for the reason that the sponge-lead gradually shrinks, tending to cohere and close up the pores, and approach the condition of ordinary metallic lead. Also the pores become clogged with sulphate or impurities in the electrolyte, thereby causing a gradual diminution in the capacity of this electrode, so that in the course of a year or two its capacity diminishes to a point where it will be equal to, or less than, that of the peroxide electrode.

The capacity of the Planté peroxide electrode diminishes but little, if at all, because each charge tends to form peroxide from the underlying lead, and any of this active material which is shed off or falls away from the plate tends to be replaced by a new growth of peroxide. Pasted positives slowly lose capacity, but the loss is very gradual.

The diminution in the capacity of the negative plate can be prevented, in the case of pasted plates, by mixing with the applied active material certain inert substances which give a permanent porosity to the material such as pulverized coke, porcelain, and materials of a like nature.

The decrease in capacity of the sponge-lead electrodes with time is indicated by Fig. 27. It will be observed that plates having a thin layer of active material lose their capacity more rapidly than do those having thick layers, and, also, the decrease appears to be proportional to the number of discharges, and not to the number of ampere hours discharged.

Only recently has it been found possible to treat Planté negatives so that they maintain their capacity. Bijur* has devised a process whereby the negative plates are immersed in a solution of some inert element, such as sugar, and this solution allowed to penetrate throughout the mass of the sponge-lead, after which the plates are heated to a temperature of about 300° C., which is high enough to carbonize the sugar and yet is below the melting point of sponge-lead. This treatment leaves the pores either filled or lined

* American Patent Reissues Nos. 12871 and 12872.

with porous carbon, and tests covering about two years show that there is no diminution in capacity. This treatment, when applied to ordinary Planté plates which have lost a large part of their

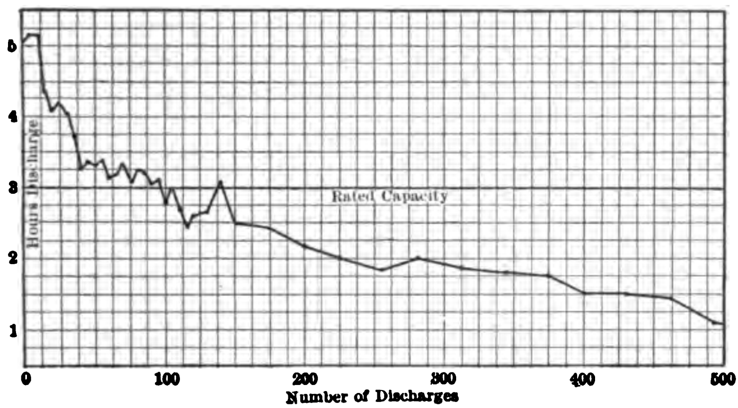


FIG. 27. Decrease in Capacity of Planté Negative Plates with Number of Discharges.

capacity, causes them to regain their normal capacity. The curve in Fig. 28 shows the loss of capacity of an ordinary Planté negative and its subsequent increase in capacity after being treated by this process, which is known in the trade as "permanizing."

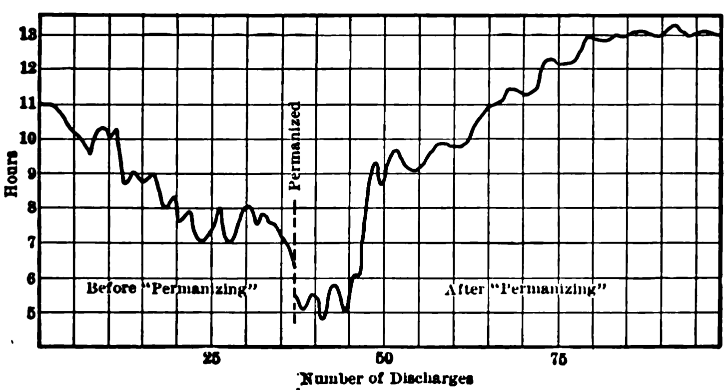


FIG. 28. Loss of Capacity of Planté Negative Plate and Restoration by Permanizing.

In general, the capacity of the positive plate increases for a time, except in cases where an excessive layer of active material is initially formed, in which case it will begin to shed off very shortly

after the cell is put into commission. This loss will cease after the thickness of the active material has been somewhat reduced. The capacity then remains, substantially, stationary, the active material gradually shedding and being replaced by the formation of PbO_2 from the underlying base lead of the plate. When the base lead is finally used up, the loss of peroxide can be no longer compensated for, and the capacity then begins to decrease until the plates disintegrate.

The capacity of the pasted positive plates usually increases for a short time after being put into service, which increase is due to an improvement in the porosity of the active material with use. After a maximum porous condition is reached, the capacity then begins to diminish, the active material gradually shedding off, and thereby diminishing in quantity; while the supporting grid, which is usually an antimony and lead alloy, does not furnish any base lead for the formation of new lead peroxide.

The capacity of negative plates, whether Planté or pasted, may rise with a few discharges, owing to increase in porosity, after which they continuously decrease, unless permanized and their porosity thereby maintained.

Jumau claims that the increase in capacity of Planté positive plates is attributable to changes in the crystalline structure of the lead peroxide. When first formed, the crystals of PbO_2 are comparatively large. On discharge, sulphate is formed and the molecules still further increase in size. On charge the sulphate is removed, and this leaves these large crystals with multitudinous small pores, which is the equivalent of a number of small crystals. This increases the porosity of the peroxide, and therefore the capacity of the cell.

The principal factor which causes a variation in the capacity is the rate of discharge. The capacity of different types of plates with different discharge rates has been studied by Wehrlin. Curves shown in Fig. 29 are those for Planté plates and indicate the variation in capacity at different rates of discharge. Each curve represents the capacity obtainable for a given value of the terminal voltage, these final potentials ranging from 1.80 to 1.95, as indicated by the numerals at the end of each curve.

Figure 30 shows variation in capacity of pasted plate cells with rates of discharge, and various terminal voltages, while Fig. 31 shows similar curves for the so-called "mass plates,"

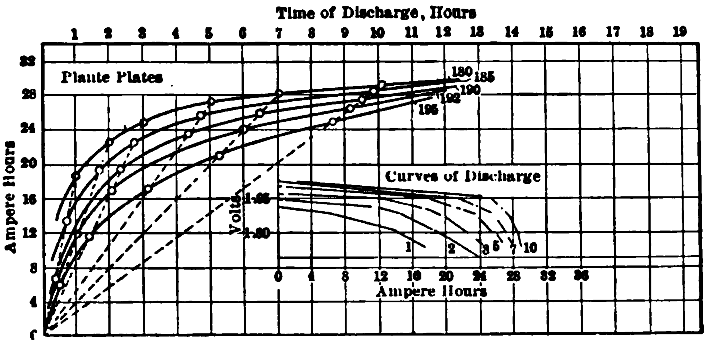


FIG. 29. Variation in Capacity with Rate of Discharge. — Planté Plates.

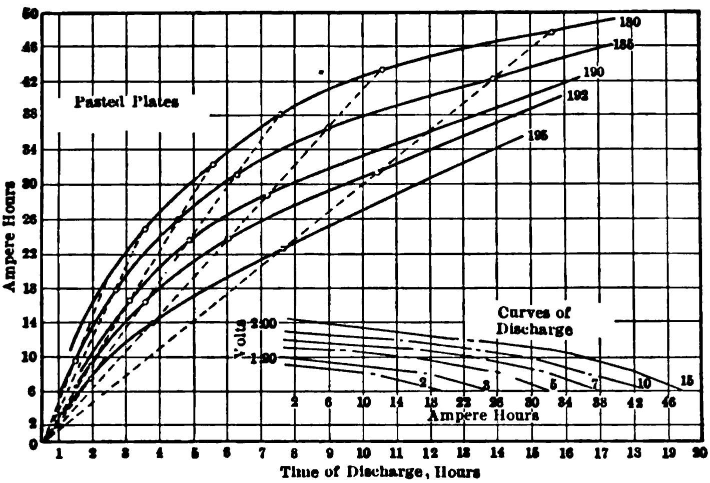


FIG. 30. Variation in Capacity with Rate of Discharge. — Pasted Plates.

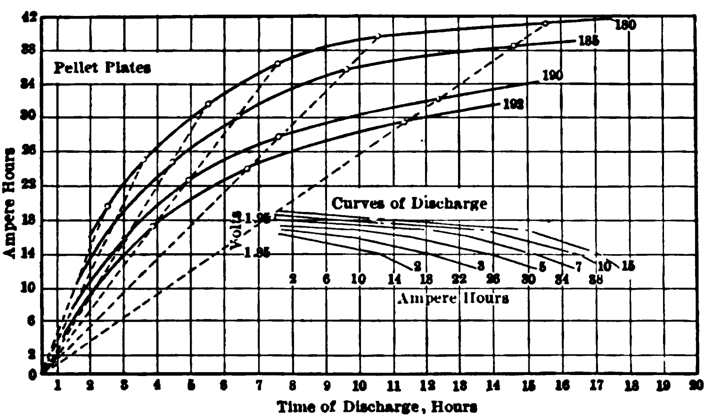


FIG. 31. Variation in Capacity with Rate of Discharge. — Pellet Plates.

made up of large pellets or slabs of active material contained in a framework.

These curves are instructive and should be carefully studied, as they are indicative of changes in the most important factor that the engineer has to consider in designing plates or storage battery equipments.

Peukert* has formulated a law whereby the capacity of a cell at different discharge rates may be computed. His formula is of the general form:

$$I^N \times t = C \tag{41}$$

in which

- I = current rate of discharge,
- n = an exponential factor which differs for different types of plates,
- t = time of discharge, in hours,
- C = a constant.

From this equation it is clear that the smaller is n, the less is the change in the ampere-hour capacity of a cell with varying rates of discharge. His experiments show that n has the following values:

Planté plates	1.30 to 1.39
Pasted plates	1.51 to 1.72

If the capacity of any cell at two different rates be known, the exponent, n, may be determined for that particular cell.

Since $$I^N \times t = C,\ I_1^N \times t_1 = I_2^N t_2 \tag{42}$$

in which I_1 is the current which is discharged for the time t_1, and I_2 is the current which the cell can supply for the time t_2.

From equation, (42)

$$\log t_1 + n \log I_1 = \log t_2 + n \log I_2$$
$$n(\log I_1 - \log I_2) = \log t_2 - \log t_1$$

$$n = \frac{\log \frac{t_2}{t_1}}{\log \frac{I_1}{I_2}}. \tag{43}$$

* Elektrotechnische Zeitschrift, No. 20, pages 287–897.

The capacity at any discharge rate I_x may be found by solving for C, using the known quantities I_1, n and t_1, or I_2, n and t_2, then,

$$t_x = \frac{C}{I_x^N} \tag{44}$$

and,

$$I_x^N = \frac{C}{t_x} \tag{45}$$

Capacity at rate $I_x = t_x I_x$ ampere hours.

It is not to be understood that, when cells are discharged at a high rate, and less energy is obtained from them than when discharged at slow rates, that the total available energy in the battery has been taken out of it. If the cell be allowed to stand for a few hours, it will be found that it will give an additional discharge at the normal rate, and the sum of these two discharges will very nearly equal the output at the normal rate.

No accurate general rule can be given for the rate of capacity decrease, with rate of discharge increase, as the various causes effecting the decrease will vary in degree with different types of plates and also with different temperatures.

If the plates are of large active area, *i.e.*, finely subdivided, the layer of active material thin and porous, and the electrolyte ample in quantity and of proper density, so that the rapid formation of a surface of sulphate is prevented, it is obvious that the decrease in capacity will be less with high discharge rates than is the decrease with plates carrying the same quantity of active material in a thicker layer of less porosity and surrounded by a small quantity of electrolyte of high density.

Though there is no practical law applicable to every type of cell, it is important that some rough general rule be formulated in order that the engineer may be able to intelligently design a plant to meet conditions of load without battery exhaustion. The following tables give the variation in capacity with different discharge rates of three types of batteries, viz.: The Planté, positive and negative; the Planté, positive and sponge-lead pellet negative, and the Faure positive and negative, the data being taken from experiments on three different makes of cells.

TABLE XI.

PERCENTAGE OF CAPACITY VARIATION AT DIFFERENT DISCHARGE RATES.

Rate.	Per cent of capacity at 8-hour rate.		
	Planté. (1)	Planté pos. pellet neg. (2)	Pasted. (3)
8 hour	100	100	100
7 "	99	97	96
6 "	96½	93½	92
5 "	93	89	86½
4 "	88	83	80
3 "	80	75	72
2 "	70	65	61
1½ "	63	57½	53½
1 "	55	50	46

From these data are plotted the three curves shown herewith in Fig. 32 with the rates of discharge as the abscissæ and percentage of capacity as ordinates. These curves correspond in general form to those obtained by Wehrlin.

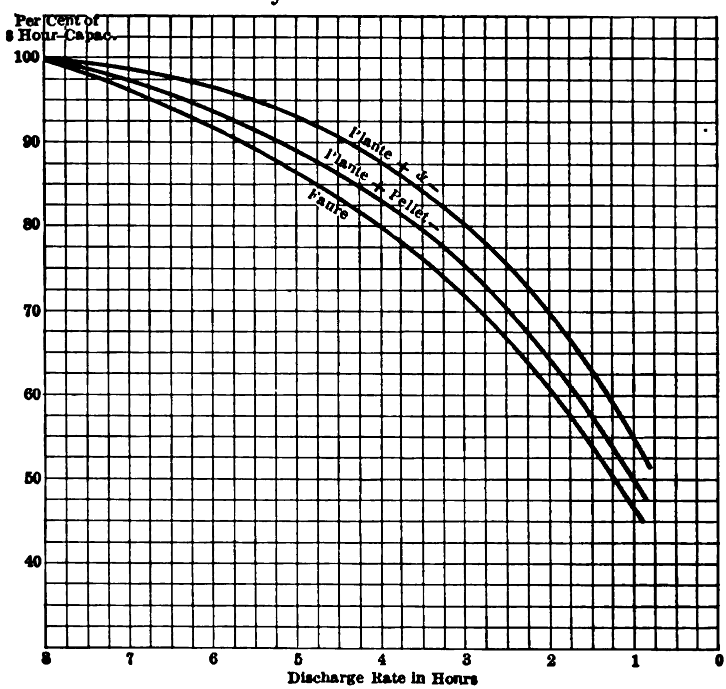


FIG. 32. Variation in Capacity of Various Types of Plates with Discharge Rate.

The table and curves show that the capacity percentages of the Planté positive and pellet negative as given in the second column of the table may be taken as fair averages for making calculations of battery required to meet given conditions. Greater accuracy than this is not necessary, as the other variables, particularly temperature, make an exact calculation practically impossible. It is, however, advisable to secure from the manufacturer a set of discharge curves of his particular battery before laying out a plant.

A simple, practical formula for computing the normal capacity of a cell at the 8-hour rate when its output at some other rate is known, though not so accurate as that of Penkert, is

$$I \times T \times K = A.H.$$

in which I = Discharge current in amperes,
T = Time of discharge in hours,
K = Factor in table corresponding to rate of discharge,
A.H. = Capacity in ampere hours of cell at 8 hour rate.

TABLE XII.

TABLE OF FACTORS "K."

Rate	K
8	1.00
7	1.03
6	1.07
5	1.13
4	1.21
3	1.33
2	1.54
1½	1.74
1	2.00

Conversely, if the capacity of a battery at the 8-hour rate is known, its capacity at some more rapid rate is $\frac{A.H.}{K}$, in which K is the factor in the table corresponding to the time of the higher discharge rate.

These factors are principally of value in computing the capacity of battery required to discharge at varying rates for a given length of time, an example of which is given in a subsequent chapter.

Since the capacity is dependent upon the length of time which a battery can continue discharging before the voltage falls to some

fixed value, it is obvious that for a given set of electrodes, the capacity for any rate of discharge is dependent on the rate of diffusion, which in turn is dependent on the thickness of the active material and its porosity, which two factors fix the rate of diffusion. One evidence of this is the fact that with increase in rate of discharge, the capacity of the positive plates diminishes more rapidly than the negatives, for the reason that the lead peroxide is not so porous as the sponge-lead, and the diffusion takes place more slowly in the positive plates.

To show the dependence of capacity on the rate of diffusion, Liebenow made an experiment, the apparatus employed being shown in Fig. 33. A vessel is set inside a larger vessel, the smaller having a hole cut in its side and a peroxide electrode sealed into the opening. This electrode was of such a character that with a slight pressure, electrolyte would be forced through it, passing through the pores of the active material. A negative electrode was suspended inside the small vessel, which was then filled with electrolyte. The static head forced the electrolyte through the positive plate, the liquid being caught in the outer vessel. Discharges were taken between the two plates: first, with the inner and outer vessels filled to the same level, so that the static head on each side was in equilibrium and there was no pressure to force the electrolyte through the positive plate; after this, the discharge was taken with the outer vessel only partially filled, thus producing a static head to force the acid through the plate. On the first discharge, without forced circulation, 14.4 ampere hours were obtained. On the second discharge, with forced circulation, 41.6 ampere hours were obtained from the same pair of plates, or a capacity nearly three times greater than the plates could furnish when dependent on diffusion only, for their supply of electrolyte.

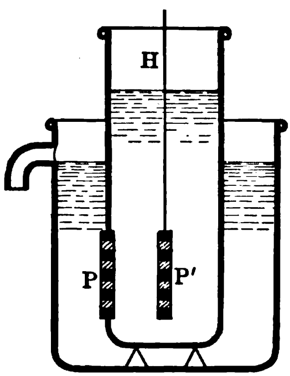


FIG. 33. Test for Increase of Capacity with Circulation.

Duncan and Wiegand * made some experiments in 1889 to determine the rate of diffusion. They soaked plates weighing about 700 grams in electrolyte having a density of 1.175, and then

* Transactions A. I. E. E., Vol. VI, page 217.

immersed them in a vessel containing a known weight of pure water. By means of a hydrometer, they determined each minute the quantity of acid which had been diffused from the plate into the water. Both lead peroxide and sponge-lead electrodes were tried, and each was tested after being fully charged, and afterwards were discharged and again tested.

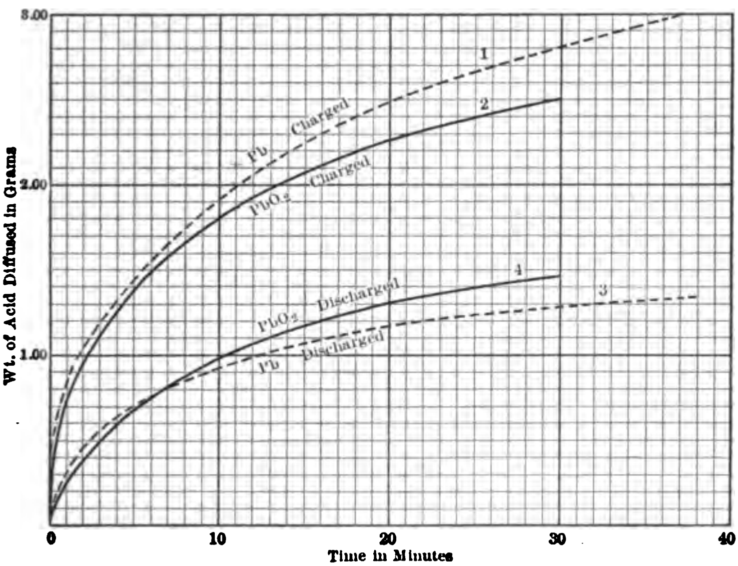


FIG. 34. Rate of Diffusion in Pores of Active Materials.

In Fig. 34 are shown curves which give the results of these tests, and they indicate that the rate of diffusion is at first very rapid, and then gradually diminishes as the difference of density between the external and internal masses of electrolyte becomes more nearly equalized.

Curves 1 and 2 show the rate of diffusion for the Pb and PbO_2 pellets, respectively, when charged and subjected to the above described treatment, while curves 3 and 4 show the rate of diffusion when the plates are discharged. The effect of sulphation is obvious from these curves, and shows that diffusion is greatly retarded on discharge by the sulphated condition of the active material.

The capacity varies with the thickness of the plate and the density of the acid, as has been previously indicated; these two

factors are interdependent, and their combined effects are modified by the rate of discharge.

Jumau made a series of tests to determine the effect of the thickness of active material, the results of which are shown in Figs. 35 and 36. Fig. 35 shows the variation in capacity of positive plates at a number of different discharge rates, for different

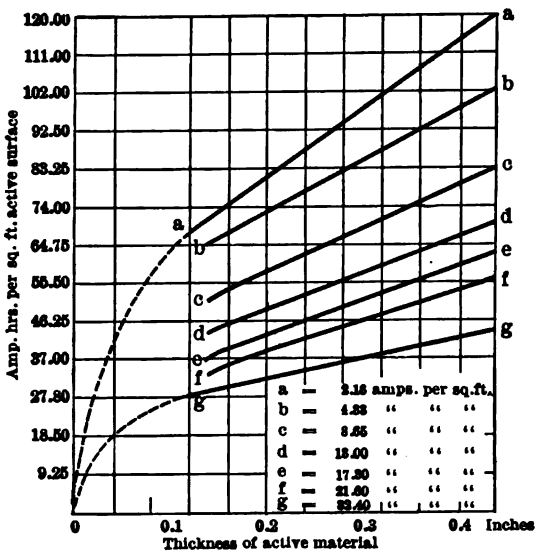


FIG. 35. Variation in Capacity of Positive Plates with Thickness of Active Layer.

thicknesses of active material, the outputs being given in ampere hours per square foot of plate surface. Fig. 36 is a similar series of curves, showing the same variations for the sponge-lead plate. From these, it is clear that the higher the rate, the less is the capacity per unit mass of active material, whatever its thicknesses, and, also, the increase in thickness of active material does not produce a corresponding increase in capacity under any conditions of practical discharge.

Liebenow has devised a formula for computing the influence ot the thickness of active material, which is approximately expressed by the equation:

$$Q = \frac{M}{1 + aI \cdot d}, \tag{46}$$

in which Q is the capacity in ampere hours, a and M are con-

stants, I is the current rate of discharge per square decimeter and d the thickness of active material in millimeters.

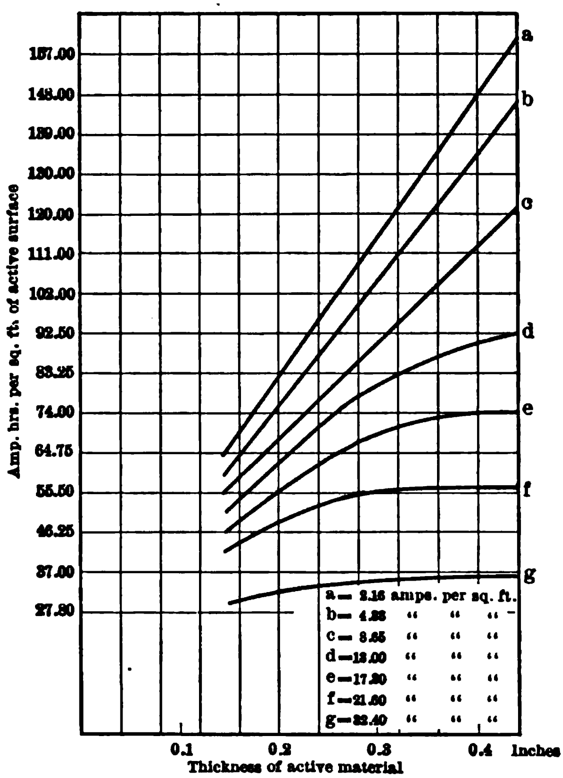


FIG. 36. Variation in Capacity of Negative Plates with Thickness of Active Layer.

Another formula showing the influence of thickness of active material on capacity, is that of Dolezalek, which is:

$$Q = \frac{3.71 + 0.438\,d}{I^{0.40}}, \tag{47}$$

in which

Q = ampere hours per square decimeter,
d = thickness in millimeters from surface to grid,
I = current per square decimeter, in amperes.

This formula is not general. It applies only to cells having electrolyte densities of approximately 1.250 and within the limits of usual practice.

The capacity is also influenced by the density of the electrolyte. For any plate having a given thickness of active material, there is some particular density at which the maximum output is obtainable, and if the acid has a greater or less concentration than this specific gravity, the capacity will be diminished. Furthermore, this concentration for maximum capacity varies for each rate of discharge.

Experiments on the influence of electrolyte density have been made by Heim, Earle, Jumau, and others. Figure 37 shows curves

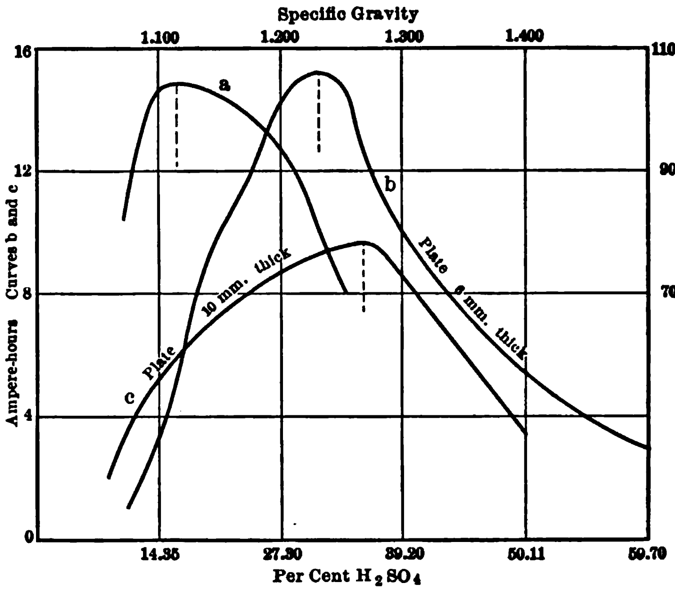


FIG. 37. Variation in Capacity of Different Plates with Electrolyte Density.

plotted from data taken from the observations of Heim and Earle.* In these is clearly shown the variation of capacity with the density of electrolyte, the maximum point shifting with change in thickness of the active material.

Jumau's experiments were much more extended, and the results obtained by him are indicated in Fig. 38. The full lines show the capacity when the cell is discharged down to 1.80 volts, while the dotted lines show the capacity at the same current rate discharged down to 1.70 volts. The rates varied from the 25-hour down to the 3-hour rate.

* Zeitschrift für Elektrochemie, Vol. II, 1895, 1896, p. 559.

The discharge rates adopted in the tests, from which these curves were taken were:

A and a	25 hour rate giving	11 ampere hours.
B " b	18 " " "	9.9 " "
C " c	10 " " "	8.9 " "
D " d	6 " " "	8.1 " "
E " e	3 " " "	7.3 " "

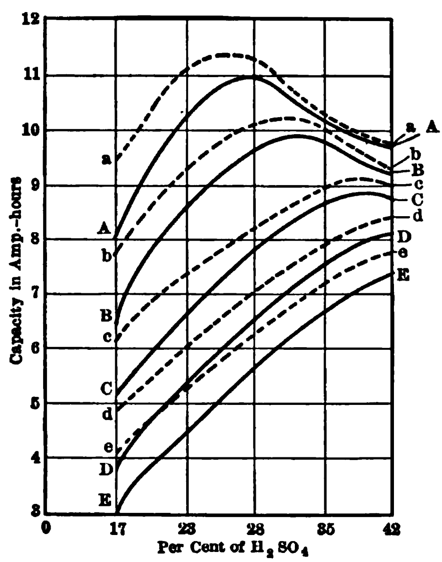


FIG. 38. Variation of Capacity of Different Plates.

It is to be noted that the full and dotted curves have the same general form.

The plates on which these tests were made were of the pasted type, made up of grids having a number of small rectangular holes passing from face to face, in which was inserted the active material, in the form of plugs, the thickness of these plugs being 7 millimeters.

As may be seen, the maximum capacity at the lowest rate was obtained with electrolyte having about 27% H_2SO_4, while the maximum capacity for the highest rate was obtained with 41% electrolyte. These curves show how widely the density of electrolyte for maximum capacity changes with change in dis-

charge rate, and indicate that the higher the rate, the higher must the density be also, to give the maximum capacity.

It might be supposed that the higher the electrolyte density the greater would be the capacity in any case. The reason a maximum point exists is, if the acid be too weak, the concentration rapidly falls with discharge, and the capacity is therefore decreased. If the acid density, however, is too high, the resistance of the elements increases, because the internal resistance of the active material; after sulphation begins, is dependent largely on the resistance of the mass of acid in the pores of the active material.

Since the minimum resistance of sulphuric acid solutions lies between the specific gravities of 1.220 and 1.230, the electrolyte having the minimum *average* resistance will be that which most nearly keeps within these limits throughout its range of gravity changes. Obviously, the thicker the active material, or the higher the rate, the less opportunity there is for diffusion, and therefore the higher must be the initial density of the electrolyte to keep most nearly to the range of minimum electrolyte resistance.

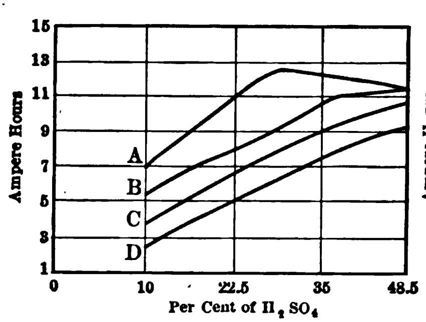


FIG. 39. Variation of Capacity of Different Positive Plates with Electrolyte Density.

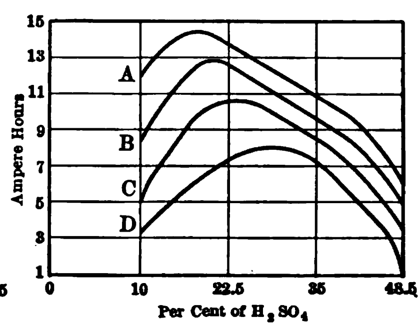


FIG. 40. Variation of Capacity of Different Negative Plates with Electrolyte Density.

Figures 39 and 40 show the variation in the capacities of the individual electrodes of the cell in the foregoing experiments. Fig. 39 represents the changes in capacity of the positives, while Fig. 40 represents the changes in the negatives for the various discharge rates and electrolyte densities.

As may be seen, the maximum point is more sharply defined

and the capacity sinks more rapidly on either side of the maximum point in the case of negatives than with the positives.

Other experiments of Jumau are shown in Figs. 41 and 42. The first of these two sets of curves represents discharge of a certain cell at a low rate with three different densities of electrolyte: namely, 1.310, 1.220 and 1.110, while the curve shown in Fig. 42 indicates the capacities obtainable from the same cell with the same densities of electrolyte at very high rates of discharge.

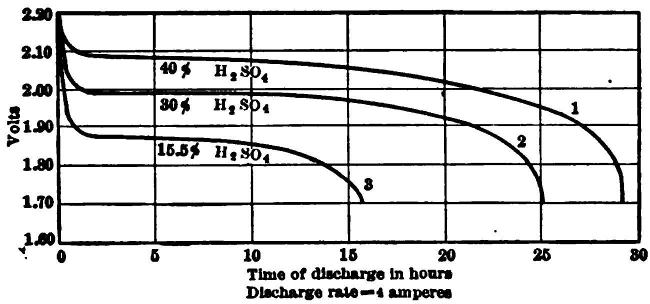


FIG. 41. Variation of Cell Capacity with Different Electrolyte Densities.

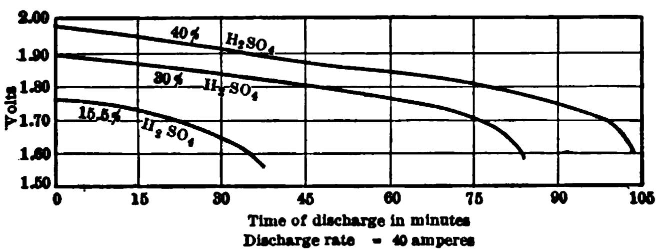


FIG. 42. Variation of Cell Capacity with Different Electrolyte Densities.

If this experiment were considered alone, it would appear that the higher the electrolyte density, the greater is the capacity, but the other experiments of Jumau, together with those of Heim and Earle, before given, show that for each rate there is some particular density at which the maximum capacity is obtainable.

Since the active material is more porous at high temperature than at low, and the resistance of the electrolyte is diminished and the diffusion increased with rise of temperature, it follows that the capacity is augmented with increase in the cell temperature. Taking the capacity at 60 degrees F. as the standard, it will

increase or decrease from 0.7% to 1.5% per degree F., above or below 60 degrees, depending on the character of the electrodes. The change is greater with pasted electrodes having thick layers of active material than with the thinner layers of Planté plates.

The capacity is reduced by local action or internal discharge. The density of the electrolyte is the best guide as to the condition of charge of the plates. Specific gravity readings will show how much of the SO_4 has been absorbed, and therefore how far the sulphation of the active material has proceeded.

In all the foregoing discussions, it has been assumed that a sufficient quantity of acid is always present. In certain types of cells, however, such as those used for electric vehicle propulsion, there may be a deficiency of acid, in which case the capacity will fall off more rapidly with a given rate of discharge than has been indicated in preceding parts of this chapter.

Following is a table showing the weights of several sizes of cells made by various companies in America and corresponding weights of complete cell per ampere hour. Capacities given are at the 8-hour rate.

TABLE XIII.

Trade Name.	800 Amp. hr.		1600 Amp. hr.		2400 Amp. hr.		4000 Amp. hr.	
	Wt. Total in lbs.	Lbs. per A. Hour.	Wt. Total in lbs.	Lbs. per A. Hour.	Wt. Total in lbs.	Lbs. per A. Hour.	Wt. Total in lbs.	Lbs. per A. Hour.
Westinghouse....	700	0.875	1125	0.704	1555	0.65	2455	0.614
Gould...........	495	0.618	925	0.577	1355	0.565	2215	0.555
Elec. S. B. Co....	482	0.605	829	0.518	1207	0.502	1921	0.481
Bijur...........	469	0.588	858	0.558	1325	0.532	2018	0.502
National........	544	0.68	986	0.617	1428	0.595	1871	0.478

Col. R. E. Crompton, in 1890, called attention to the fact that cells exposed to the light of the sun or of arc lamps give a lower capacity than when kept in the dark.

M. U. Schoop, in 1900, made a series of experiments in which he found that the action of sunlight on newly applied lead peroxide was to lighten its color to a reddish hue, and from this fact he reasoned that a chemical change was produced. Dr. Franz Peters, how-

ever, made a similar experiment after Schoop's announcement of the change effected by sunlight, and found that the color was changed as Schoop had stated but the chemical composition had not been affected.* Peters therefore ascribes the color change to a physical molecular effect and not to any chemical reaction. It however is probable that this physical change has the effect of reducing the capacity as originally discovered by Crompton.

* Centralblatt für Accumulatoren, No. 16, 1900.

CHAPTER IX.

INTERNAL RESISTANCE.

THE internal resistance of a cell is made up of four factors, namely: (1) the resistance of the metal of the supporting grid; (2) the resistance of the active material itself; (3) the resistance of the electrolyte contained in the pores of the active material, (4) and the resistance of the mass of electrolyte surrounding the plates. All of these are practically negligible, except the resistance of the active material and the electrolyte in the pores of the plates. A cell in good condition has an internal resistance which is very small and the I^2R loss during discharge is seldom over 5%, and at low rates may be as small as 2%.

The internal resistance varies with the temperature of a cell, decreasing as the temperature increases.

Also, as might be expected from considerations of dilution of acid in the pores and sulphation on discharge, the resistance rises until at the end of discharge a maximum is reached which is from two to four times as great as the value at the beginning of discharge; conversely the resistance decreases from beginning to end of charge.

It is practically constant for any current rate of charge or discharge, but varies as the amount of charge in the cell changes. The curves shown in Fig. 43 indicate the manner and degree of this variation. It is seen that the resistance drops on charge until a minimum is reached, after which the change is almost inappreciable, the resistance becoming practically constant.

On discharge, the resistance begins to rise slowly, and then more rapidly as the discharge proceeds. The maximum resistance may be very high, depending on how far discharge is carried. If continued to the point of complete sulphation of the plates, the resistance may be many ohms.

Methods for measuring internal resistance are given in the chapter on Testing.

The most complete study of this subject has been made by

Dolezalek and Gahl.* Their researches show that for a charged cell nearly all of the resistance is due to the electrolyte, the resistance of the other parts not being appreciable.

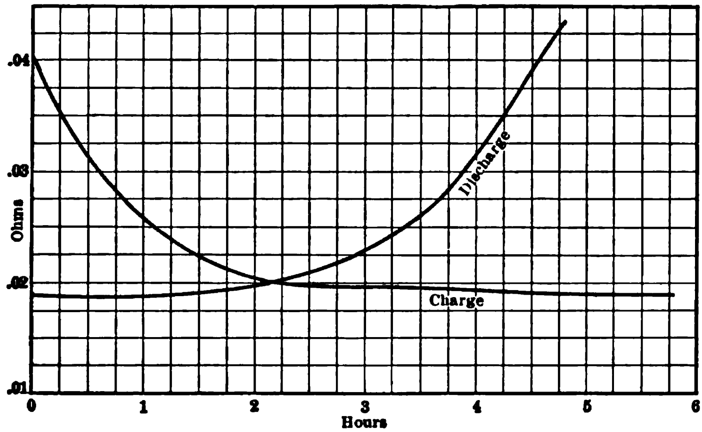


FIG. 43. Internal Resistance of a Cell.

Figure 44 shows curves of variation in the resistance at the positive and negative plates while discharging. These show that the resistance rises with discharge, just as has been previously indicated in this chapter; the principal increase, however, takes place at the positive electrode, the negative changing but little.

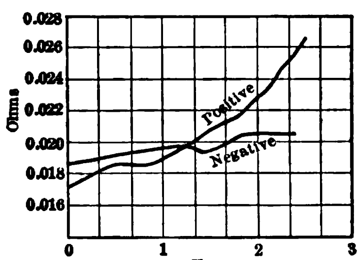


FIG. 44. Internal Resistance of Individual Electrodes.

Figure 45 shows a series of curves of variation of the internal resistance at the positive plates. Curves I and II are for positive plates of the pasted variety, while curve III is that for a Planté plate. The upper curves, 1, 2 and 3, are the discharge curves for these plates, and from a comparison of the two sets of curves, it becomes obvious that the final drop in electro-motive force

* Zeitschrift für Elektrochemie, Vol. VII, 1901, page 429.

follows exactly the increase in the internal resistance. This is a confirmation of Wade's theory, referred to in Chapter VII, namely: that the final drop in electro-motive force of a cell is due almost entirely to the increase in the internal resistance.

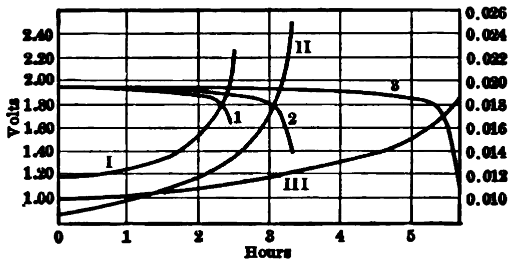


Fig. 45. Discharge and Internal Resistance Curves.

When the rate of discharge is high, the internal resistance at the positive plate rises more rapidly than when the rate is low, and for this reason it has been believed that the internal resistance is dependent on the rate of current flow. This, however, is by no means true. The internal resistance is dependent on the amount of lead sulphate mixed or compounded with lead peroxide, the density of the acid in the pores, and the extent to which a masking layer of sulphate has been formed on the outer surface of the plates.

Obviously, the conditions which produce high internal resistance will be attained more quickly and carried to a further extent at high current rates than with low; and this is the manifest

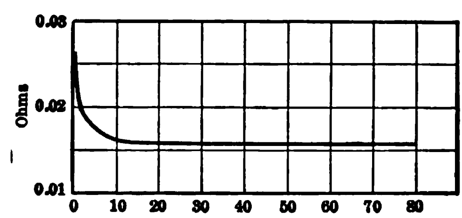


Fig. 46. Reduction of Internal Resistance After Discharge.

reason for the more rapid rise of the internal resistance with high current rates of discharge. The potent factor in producing a high internal resistance is the diminution in the density of the acid in the mass of the active material. This is clearly shown by the curve in Fig. 46, which is plotted from a series of readings

taken from a discharged cell, the first observation being made immediately after opening the circuit at the end of discharge, the subsequent readings being taken at intervals of a few minutes. As may be seen, within ten minutes the internal resistance falls to practically its normal value and then remains constant. Clearly, the only effect which could have taken place was the diffusion of the strong acid from the surrounding body of electrolyte into the pores. The diffusion is greatly retarded by the layer of lead sulphate which forms on the surface of the active material during discharge.

In this experiment, the investigators discovered that there is no increase in the internal resistance of a cell at the end of charge, because of the liberation of free gases, which is contrary to the long maintained opinion of various authorities.

The mere liberation of gases does not appreciably increase the resistance. If, however, the electrodes are so constructed that pockets are formed in which the gases may accumulate and thus shield portions of the plates from the electrolyte, the internal resistance will be augmented.

The ohmic resistance is not the only cause of variation in the potential at the terminals of a cell with variations in charge and discharge. Polarization effects — which are counter electromotive forces produced by the electro-chemical action of the current — also act with the resistance to raise the potential on charge and to lower it on discharge.

The apparent resistance due to the combined action of resistance and polarization is termed " Virtual Resistance " and it is numerically equal to the difference between the voltage of charge and that of discharge, divided by the sum of the current flows on charge and discharge. This is also equal to the difference between the voltage on open circuit and that on discharge, divided by the current flow. It is, of course, understood that the excessive rise when near gassing on charge, and the large drop near the end of discharge, are not determining quantities in this connection. Both are terminal conditions, and though they must be taken care of when batteries are used on constant potential circuits, they do not occur in the general operation.

As will be seen later, certain coils on booster field windings are for the purpose of producing an electro-motive force in the armature, which just compensates for this variation in the cell voltage.

Hence it becomes important to settle on some value which can be used in these calculations.

The author has made a number of experiments to determine the potential drop in cells with varying rates of discharge and has discovered that the drop is practically a constant for any size or type of cell for a given *time rate* of charge or discharge, and a given state of battery charge.

The following table and the curve shown in Fig. 47 show how the drop is related to the rate of discharge and is independent of the

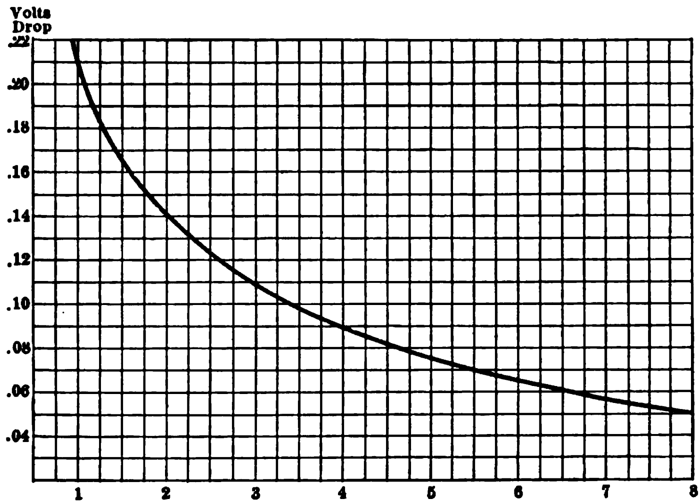


FIG. 47. Drop in Cell Voltage with Rate of Discharge.

size or type of cell. This latter is, of course, not strictly true, but is nearly enough so for all practical purposes. Accuracy requires a test of the particular battery or type on which information is desired, but for usual engineering calculations this table and curve given herewith are sufficient. Figures are for battery *one-third discharged.*

TABLE XIV.

	Drop.
8 hour rate	.05 volts
6 " "	.065 "
4 " "	.09 "
3 " "	.11 "
2 " "	.14 "
1½ " "	.185 "
1 " "	.21 "

These values are for a continuous discharge of two minutes or more at the rates mentioned. Usually, however, the duration of the maximum rates is only momentary and the values reached on the 1, 1½ and 2 hour rates will not be over 70 or 80 per cent of the figures given in the table.

In the booster formulæ before mentioned, the factor referring to compensation for drop or rise at the battery terminals appears as the internal resistance of the cell, and it is necessary to put the data in this form, which may be done by the following formula:

$$R = \frac{.09}{D}, \tag{48}$$

in which

R = virtual internal resistance of cell,
D = 4-hour discharge rate.

Any value of drop given in the table may be used if it be divided by the current corresponding to the rate to which it appertains. Thus, in a cell with a 4-hour rate of 100 amperes, the virtual internal resistance would be

$$\frac{.09}{100} = .0009 \text{ ohm.}$$

This drop will also vary with temperature, the condition of cell and electrolyte density, and the figures given are *only averages.*

It must be remembered that in case of a number of cells, joined in series, the ohmic resistance of the connectors and leads to the booster — including switch contacts and other joints — must be added to the virtual internal resistance to obtain the virtual resistance of the battery circuit.

CHAPTER X.

INTERNAL DISCHARGE.

INTERNAL discharge, or local action, means a loss of energy in the cell, and is caused by local currents in either of the electrodes which flow from one point to another, by reason of a difference of potential which exists in different parts of the same plate. There are two kinds of local action: One is the normal internal discharge which may occur in a cell in which there are no impurities in the materials, either of electrodes or electrolyte, and the other is an abnormal discharge which is caused by impurities in the cell.

The normal internal discharge takes place only at the end of charge as will be later explained. It is of short duration and seldom of practical importance.

The term "local action" means the continuous, internal self-discharge and consequent reduction in capacity and the sulphation of the electrodes.

Any marked local action may nearly always be traced to impurities in electrolyte, although they are occasionally found to proceed from impurities in the active material itself. Some of these impurities will attack only the negative plate, while certain others will attack both electrodes.

Lead is slightly attacked by sulphuric acid, the degree varying with the strength of the acid. Lead in the presence of H_2SO_4 is always covered with a very thin layer of lead sulphate, which protects the underlying metal. For this reason the sponge-lead of the negative electrode will be partially sulphated if the acid density be too high.

Local action of any kind increases rapidly with the acid concentration and also with temperature.

The sponge-lead is more susceptible of injury than the peroxide, owing to its finely divided state and being a highly electro-positive metal. Because of its porosity when fully charged, — that is, when in the state of pure sponge-lead unmixed with sulphate, —

it will, if exposed to air, oxidize so rapidly as to become hot, and is thereby hardened, after which it can only be reduced again to a useful condition by a long, developing charge such as was required for its original formation.

The metallic impurities in the acid can cause no local discharge on the positive plate unless they be such as are easily oxidized. These act as oxygen carriers from anode to cathode, and thus cause a transfer of charge, which results in gradual internal discharge of both electrodes. All metals which are not precipitated on the negative plate and which occur in several degrees of oxidation have this property. Iron and manganese are examples, as will later be explained.

Certain lead attacking acids or their salts, such as are used in the formation of the peroxide plates, will continue the formation process if introduced into the cells. This will cause a continuous increase in the cell capacity, but at the expense of the life of the plate, which becomes eaten away.

A continuous increase in the capacity of a cell after the first 30 or 40 cycles of charge and discharge is an indication of the presence of some acid or salt of an acid, which in solution forms a lead dissolving electrolyte.

At the positive plates there is but little chemical action of the electrolyte on the lead peroxide. The action of superoxide compounds, however, formed on charge, may be appreciable. Thus, oxygenated water, H_2O_2, transforms lead peroxide to lead hydroxide, which combination is accompanied by the release of oxygen, thereby tending to reduce the peroxide to a state of lower oxidation. This explains the reason why a positive electrode which is not attacked by ordinary electrolyte, if charged in water, has its active material gradually changed to a hydrate of a lower oxide, which forms in white flakes, and by reason of its great expansion detaches itself in particles from the surface of the electrode and floats on the surface of the liquid.

Also, persulphuric acid, $H_2S_2O_8$, decomposes PbO_2, forming $PbSO_4$ and releasing O.

Some authorities hold that the oxygen which comes off from the PbO_2 plates immediately after charge has ceased, is due to these combinations, and its appearance shows that an initial sulphation is taking place, automatically and independently of the discharge of any external current.

The possibility of any such phenomenon is very remote. The more rational explanation of the release of free oxygen is that a prolonged charge completely reduces the sulphate in the pores of the active material, thus allowing the electrolyte to penetrate to the metal of the supporting grid, which is normally protected by the sulphate which lies deep in the pores near the grid and shields it from the electrolyte.

When the electrolyte is in contact with both the leaden grid and the lead peroxide of the active material on it, a local couple is formed which produces a discharge of the positive active material and the rate of discharge is naturally most rapid in those portions nearest the grid.

In consequence the peroxide in the far interior of the pores is converted into sulphate, the action being accompanied by the formation of water and the release of oxygen. This is shown by the equation,

$$PbO_2 + H_2SO_4 = PbSO_4 + H_2O + O.$$

This process continues until a shield of sulphate is formed which shuts off the electrolyte from access to the grid.

The local action between the grid and the active material of positive electrodes is greater with plates having pure lead grids than with those having grids of lead-antimony alloy. Some investigations made by Robertson show that these actions at the positive electrode are principally theoretical and exceedingly small in practice.

The discharge of the negative electrode by metallic impurities proceeds from the formation of a local voltaic couple on the negative plate by the deposition of the injurious metal on the plate, and since the two elements of this local couple are in contact it is short-circuited.

If the deposited metal is more strongly electro-positive than sponge-lead, current will flow from the metal through the electrolyte to the sponge-lead of the negative electrode. This tends to liberate hydrogen at the negative plate and thus more strongly charge it. Therefore in this case the negative plate would not be discharged.

If, however, the metallic impurity is more strongly electronegative than the sponge-lead, the current through the short-circuited local couple flows from sponge-lead through the elec-

trolyte to the metallic deposit, releasing hydrogen at the latter, while oxygen is liberated at the sponge-lead.

This action produces lead sulphate, thereby discharging the negative electrode.

Hence it follows that any metal which is electro-negative to sponge-lead, and in conjunction with it produces a couple having an electro-motive force sufficiently great to release hydrogen on the intruding metal, will cause a local discharge of the negative plate.

The essential conditions which must be fulfilled in order that local action may take place, are: The electrolyte must be in contact with both the elements which form the active couple; the metallic impurity and active material must be in contact with each other; the difference of potential between the two elements which form the local voltaic couple must be sufficiently great to decompose the electrolyte.

Dolezalek made a series of experiments to determine the electro-motive force necessary to release hydrogen on various metals in ordinary battery electrolyte.

In order to make these tests it was necessary to use the so-called hydrogen electrode. This is made of platinum covered with platinum black (or finely divided oxide of platinum) and which latter substance possesses an abnormal power to occlude gasses. With this electrode saturated with hydrogen, this pole of the test couple becomes in effect an electrode of hydrogen.

When used as the positive pole with any other electrode as a negative, oxgyen is released at the former uniting with some of its hydrogen to form water, while free hydrogen is released at the opposite pole. The electro-motive force necessary to produce free hydrogen on the negative electrode is obviously the potential necessary to decompose the electrolyte with the chosen negative electrode, because there is no counter electro-motive force due to the couple itself, since one is hydrogen and the other covered with hydrogen bubbles which are continuously forming. Dolezalek found that the voltage of decomposition varies greatly with different metals. The results of his tests are given in the following table:

TABLE XV.

Platinum sponge or finely divided platinum	.005 volt.
Gold	.02 "
Iron	.08 "
Platinum (plates)	.09 "
Silver	.15 "
Nickel	.21 "
Copper	.23 "
Cadmium	.48 "
Tin	.53 "
Lead	.64 "
Zinc	.70 "
Mercury	.78 "

The difference of potential between a hydrogen electrode and one of sponge lead, necessary to release hydrogen at the sponge lead, is 0.33 volt, in electrolyte of ordinary density.

It therefore follows, that if any of the substances in Table XV, from platinum to copper inclusive and which have dissociation voltages lower than that of lead, are contained in the electrolyte and are deposited on the lead sponge, or appear as impurities in the active material, the conditions for local action will be present and self-discharge will take place.

The intensity of the local discharge will be inversely proportional to the values of the electro-motive forces required by the various metals to decompose the electrolyte. Therefore, of the elements which will discharge the negative plate, platinum will have the most and copper the least injurious effect.

It has been experimentally determined that if the solution contain one one-millionth of platinum, a rapid internal discharge of the negative plate will result.

Instances have occurred in which the acid used for electrolyte has been considered chemically pure, having been distilled in platinum vessels, and in these batteries the negative plates lost their capacity and rapidly disintegrated.

Plates which have been discharged by an appreciable quantity of platinum in the cell cannot again be made useful except by reversal. Other metallic impurities which form on the sponge-lead, in the course of time become covered over with a layer of sponge-lead and lose their power to discharge the electrode.

The presence of injurious metallic impurities is indicated by a

continuous evolution of hydrogen from the negative plates when the cell is open-circuited.

The concentration of the electrolyte has a marked influence on the rapidity of self-discharge at the lead-sponge element.

Dolezalek explains this by stating that on discharge, hydrogen is evolved around the impurities in the acid, and these act as hydrogen-electrodes and, therefore, with increase of acid concentration have their voltages also raised, and this voltage increase is extraordinarily great for variations in acid density, giving a corresponding increase in the ability to decompose the electrolyte and accelerate local action.

In addition to the impurities cited above, which are harmful to the electrodes, the following are also injurious.

(1) *Hydrochloric Acid.*

This acts on the positive electrode to form chloride of lead from the PbO_2 and this substance afterwards changes into lead sulphate in the presence of the electrolyte. This means an internal discharge of the positive electrode. Also when the lead chloride is changed to lead sulphate the HCl is released and is free to combine again with the PbO_2 of the electrode. Hydrochloric acid, if present in sufficient quantity, also attacks the sponge-lead of the negative electrode, producing sulphation, followed by the regeneration of the HCl as outlined above.

It has been found, however, that after about one month, very small quantities of HCl are neutralized by the electrolytic and chemical actions in the cell and it then ceases to be harmful. Chlorine gas is liberated to a slight extent at the positive electrode during charge, and this action, continued, destroys the HCl.

(2) *Arsenic.*

This metal has no effect on the positive electrode but tends to discharge the negative; its duration in a cell is very short, however. It gradually disappears, partly as an arsenate of hydrogen and partly as metallic arsenic which falls to the bottom of the cell.

(3) *Nitric Acid.*

This is harmful to both electrodes. While it does not cause discharge of the positive it will corrode and eat away this electrode.

It attacks the negative plate, forming nitrate of lead, which is afterwards converted into lead sulphate, the latter change being accompanied by the release of the nitric acid which again is free

to attack the sponge-lead. At one time it was believed that ammonia (NH_3) would injure a cell by being absorbed into the electrolyte and there having oxygen added to it and hydrogen abstracted by electrolytic action, become nitric acid (HNO_3). This belief has been found to be without foundation, the tendency being to deoxidize HNO_3 and convert it into ammonia.

It has been found, experimentally, that when nitric acid is present in a cell and accompanied by metallic impurities, the electrolyte becomes much warmer, on charge, than the normal heat rise, and instances have been known where this increase in temperature has been so great as to crack glass containing jars.

This abnormal temperature increase is obviously due to certain secondary chemical reactions which take place in the cell.

Excessive heating therefore indicates either a high internal resistance due to sulphate or impurities in the electrolyte. It must not be assumed, however, that all impurities will cause a noticeable rise of temperature.

(4) *Ammonia.*

Ammonia is, in itself, harmful and for some reason, as yet unexplained, causes a reduction in the capacity of the plates. It also causes "creeping" of the electrolyte over the edges of cells, by forming crystals of $(NH_3)_2SO_4$ around the upper parts of the cell, and the electrolyte, by capillary attraction, is led over the tops of the cells. Batteries should therefore never be installed near stables, refrigerating plants or chemical works.

(5) *Iron.*

This is one of the most injurious substances of all the impurities that the electrodes may be subjected to, when present in appreciable quantity. It discharges both the positive and negative electrodes and unlike the other impurities discussed is not eliminated with time, but is permanent.

Its action is that of an oxygen carrier. In the presence of PbO_2 it forms ferric sulphate in sulphuric acid, by abstracting oxygen from the positive active material. It then diffuses to the negative electrode, where it yields up its oxygen, thereby discharging the negative and changing to ferrous sulphate. In this latter condition it is ready to combine with more oxygen, which it obtains by travelling to the positive electrode. This continuous

action soon discharges both electrodes. Jumau states that 0.5% of iron in the electrolyte will completely discharge a cell in 20 days.

(6) *Manganese.*

Knorre* has shown that manganese salts, which are sometimes mixed with red lead in making up active material mixtures for pasted plates, act in the same way as iron salts to carry oxygen from the PbO_2 plate to the Pb plate.

Electrolysis forms either permanganic acid or manganic sulphate. The former travels to the negative electrode and there yields up its oxygen, oxidizing the negative active material and reducing the salt to manganic sulphate. This reduced salt travels to the positive plate which gives up its oxygen to change the salt again to permanganic acid, and the cycle of action is repeated and continuous.

A red or reddish violet coloration of the electrolyte indicates the presence of manganese.

(7) *Antimony.*

It is held by some authorities that antimony in a cell in any form or combination is detrimental to the negative plate. They maintain that where grids are made up of lead alloyed with antimony, some of the latter metal will dissolve out, in the form of antimony sulphate, travel to the negative plate, and there deposit itself, as finely divided, metallic antimony, on the surface of this electrode. A local voltaic couple is thus produced, and being short-circuited, a heavy local current flow will result, which discharges the negative electrode on which this deposit of antimony collects.

The small particles of antimony are in time covered over with a layer of sponge lead and thus become inert unless there is a continuous supply of antimony from the positive plate. The danger with antimony under this condition is that eventually there may be enough to diminish the porosity of the lead sponge active material and thereby seriously reduce the capacity of the negative plate. This has sometimes happened in batteries where the positive grids contain antimony. The lead covering effect, above mentioned, is to be explained as follows. The lead sulphate in the negative plate resulting from discharge is not abso-

* Zeitschrift für Elektrochemie, Vol. III, 1897, p. 662.

lutely insoluble but it is in dilute solution in the pores of the lead sponge. On charge it is deposited as in ordinary electrolysis, thereby covering the antimony particles. This explains the manner in which all metallic impurities, when present in small quantities, gradually become inert.

In addition to the above effects there is a very marked, peculiar phenomenon resulting from the antimony of the positive grids being precipitated on the negative plates, viz.: the difference of potential between such negative plates and the electrolyte, at the end of complete or overcharge, and consequently the cell voltage, is less than when no antimony is present. This has usually been explained by assuming that there is a considerable local discharge between sponge lead and antimony. While there is a very slight local action, and such plates may reach the state of full charge somewhat later than the positive plates in the same cell, still, on continued charge the difference in potential between the negative plates and electrolyte remains low. The low voltage is a result of the extremely fine subdivision of the antimony on the surface of the plate. The same effect is even more marked with electrolytes of dilute acids between platinum electrodes. The voltage of water decomposition with sheet platinum electrodes is approximately 2.5 volts. If the platinum is covered with a layer of platinum sponge the voltage is decidedly reduced. If instead of platinum sponge, the electrodes are covered with platinum black (extremely finely divided platinum) water may be decomposed at little more than 2 volts.

That the last mentioned effect results from antimony is clearly proved by adding antimony sulphate to the electrolyte, either in dilute solution or by sprinkling it in powdered form into the cell. A very small amount is sufficient to at once lower the charging voltage. Further it will always be noted that the voltage of cells containing positive plates with antimony grids is somewhat lower at the end of complete or overcharge, than where both sets of plates are of pure lead.

It might be presumed that antimony could be thus used to increase the efficiency of a cell. It is not, however, a practical means for this purpose, as the capacity of the negative plates would probably be affected in time, and further, the influence is only marked at the extreme end of charge. The slight amount of local action would also somewhat reduce the ampere-hour efficiency.

It is a matter of common knowledge that some of the most durable and successful storage cells have their electrodes made up of antimonious lead grids, to which is welded, or otherwise fastened, the active portion.

One manufacturing company, to whose records the author has access, has made a number of efforts to injure negative plates in their own laboratory by putting finely powerded antimony into the cells, but they have been unable to detect any appreciable change in the condition or capacity of the negative plates.

Jumau states that antimony is particularly deleterious in a case of cells which stand idle.

It has been discovered that metals which do not produce self-discharge when present in the electrolyte alone, if in company with one or more other metals of the same character, will cause rapid internal discharge of the battery. No reason has ever been assigned for this peculiar phenomenon, but it is well known that two or more metals, of nearly any kind, in the electrolyte have a deleterious effect.

Metallic impurities which are positive to sponge-lead may reduce the efficiency of a cell, due to the fact that they deposit on the negative plate in their metallic state during charge, and increase the counter electro-motive force of the cell at the end of charge, and therefore make necessary a higher charging voltage than would be required if they were not present. When charge ceases, they redissolve and do not augment the potential of the cell on discharge.

Differences of potential sufficiently great to effect decomposition of electrolyte, and therefore to produce local action, are sometimes caused by the difference in density of electrolyte in the top and bottom of a deep cell acting together with some other source of local action, which in itself would not be high enough to decompose the electrolyte.

Jumau* made a series of tests on negative plates by charging them fully and then allowing them to stand idle, immersed in the electrolyte, measurements being made after certain periods of time had elapsed. It was found that these plates became sulphated, the degree of sulphation increasing with the time.

The results of these investigations are shown by the curve in Fig. 48. Curve No. 1 is for negative plates immersed in electrolyte

* Les Accumulateurs Électriques, p. 331.

having a density of 1.32, while curve No. 2 shows the increase in percentage of $PbSO_4$ for negative plates standing in electrolyte having a density of 1.19. The much more rapid sulphation of the first set of plates, as compared with the second, is obvious from these curves, and it indicates the rapidity with which local action at the negative plates increases with increase in density of electrolyte.

Curve 5 of Fig. 48 shows the rapidity of sulphation of a negative plate standing in electrolyte having a density of 1.32 and containing 0.32% of antimony and 0.09% of iron. It will be seen that

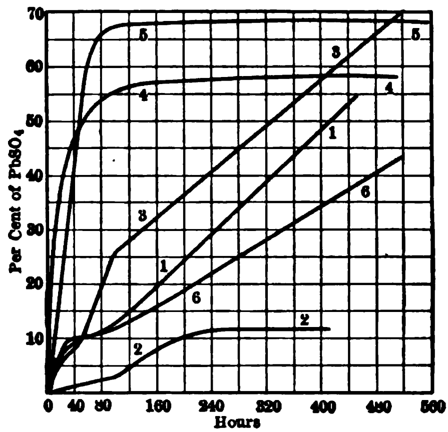


FIG. 48. Formation of Lead Sulphate in Idle Cells.

this reaches a maximum sulphation within about one hundred hours, and the amount of sulphate formed is far greater than the amount formed on the negative plate in pure electrolyte of the same density as given by curve No. 1.

The curves shown in Fig. 49 indicate the loss of charge for the positive and negative electrodes with time when immersed in an electrolyte containing 0.05% of iron and 0.072% of hydrochloric acid, 0.01% of arsenic, and 0.075% nitric acid.

It will be seen that the negative plate is much more easily and rapidly affected than is the positive. The electrolyte might be considered as fairly good, as it contains less than 0.08% of any impurity, yet the local action has completely discharged the negative plate in 120 days, and reduced the capacity of the positive 25%.

In Fig. 50 are shown curves of charge and discharge of three different negative plates which were fully charged, each in electro-

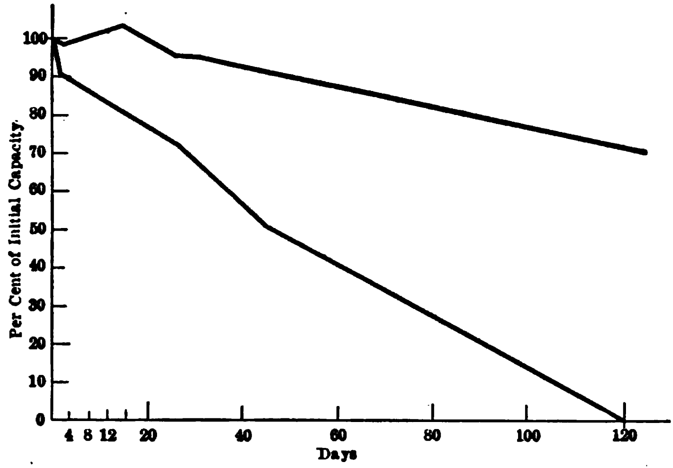


Fig. 49. Loss of Charge in Idle Cells with Impure Electrolyte

lyte containing certain impurities, the impurities in each case being different, after which the cells were set aside for twenty

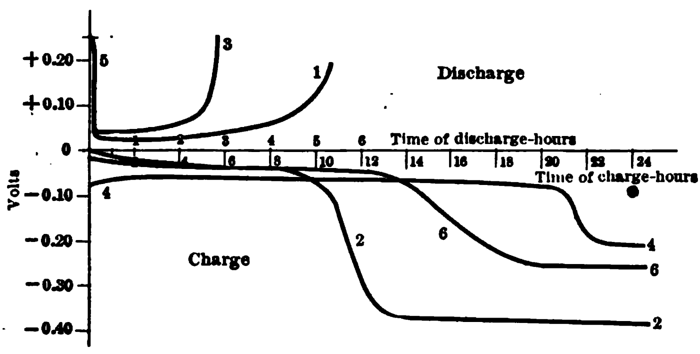


Fig. 50. Discharge Curves of Negative Plates against a Sponge Lead Electrode with Impure Electrolyte.

days and the discharges then taken. Curves 1, 3 and 5 show the potentials of these negative plates, taken while discharging, against an auxiliary test electrode of sponge lead. Curves 2, 4 and 6 show the potentials of these plates when being charged, taken against the test electrode, and the charge following immediately after the discharge and in the numbered order of the curves.

It will be noted that the discharge curve 5 gave no capacity whatever, the curve corresponding with the ordinate passing through the origin.

It is instructive to compare the ampere hours required to charge the elements and the energy yielded by them after standing. The charge rate was one half that of discharge.

Since all local actions are either chemical reactions or come from the flow of currents produced by local couples, the injurious effects are greatly augmented by increase in concentration of the electrolyte and it therefore is necessary to keep the electrolyte density within reasonable limits.

CHAPTER XI.

THE INFLUENCE OF TEMPERATURE.

THE changes in ampere-hour capacity, voltage on charge and discharge, internal resistance and efficiency with variation in temperature are surprisingly great. The change of electrolyte density with change of temperature has been previously discussed (Chapter VI).

The effects of temperature changes have been investigated by Heim, of Hannover, and others, and the experiments seem to have been carried out very completely and carefully. In Heim's experiments,* the cells were fully charged up to point of copious gassing, the voltage readings at the cell being:

At 14 degrees C.	2.70 volts.
" 30 degrees C.	2.58 volts.
" 45 degrees C.	2.52 volts.

These values show that the charging voltage decreases with a rise in temperature.

The contrary is true, however, on discharge, the voltage being higher with increase of temperature.

Figure 51 shows the charge and discharge curves of a cell at 14 degrees C. and 45 degrees C., which bring out clearly the differences in voltage mentioned. The current density was .109 amperes per square inch of positive plate.

Heim also shows that the internal resistance of the cell changes with variation of temperature, and his observations give the following results for a cell of three positive and four negative plates having a total positive plate area of 18.9 square decimeters; normal capacity, 69 ampere hours and acid density 1.22 at 18 degrees C.

Internal resistance at 14 degrees C = 0.0023 ohms.
Internal resistance at 45 degrees C = 0.0015 ohms.

* Elektrotechnische Zeitschrift, September 26, 1901.

This is a variation of .0008 ohms for 31 degrees, which is .0000258 ohms per degree.

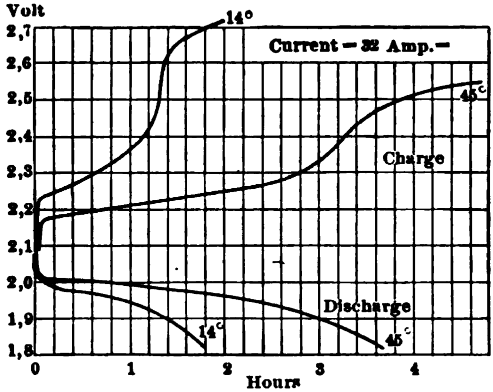


FIG. 51. Charge and Discharge Potentials at Different Temperatures.

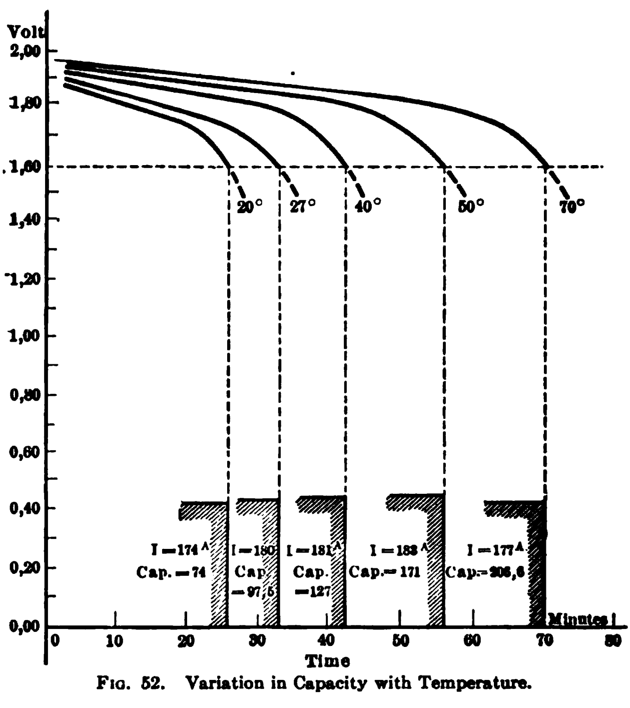


FIG. 52. Variation in Capacity with Temperature.

At 0 degree C. the internal resistance would therefore be 0023 + 14 (.0000258) = 0023 + .000362 = .002662 ohms. Taking the resistance at 0 degree C. as unity, the decrease per degree C. is .97%.

Most marked, however, is the influence of temperature on the ampere-hour capacity. Numerous tests on various sizes of cells show an increase which is practically of the same magnitude, but which does not seem to follow any general law.

Figure 52 shows the variation in ampere hours output for a battery discharged at a high rate, which rate is practically the same for each discharge, the temperature only being varied. These curves show clearly that the percentage increase is not a constant, but varies with the position on the temperature scale.

The following table gives record of Heim's tests, curves of which are shown in Fig. 51. It shows the effect of changes in temperature on the ampere hour capacity; ampere hour efficiency, electrolyte density changes, voltage and watt efficiency.

TABLE XVI.

Temp. C.	Current.		Ampere hours.			Average volts.				Densities of electrolyte at 18°.	
	Amps.	Density per sq. in.	Charge.	Discharge.	Efficiency.	Charge.	Discharge.	Volt Efficiency.	Watt efficiency.	Charge.	Discharge.
14	20	.0685	76	71	93.5					1.241	1.215
14	32	.109	60.8	57.6	94.6	2.438	1.938	79.5	75.2	1.238	1.224
45	20	.0685	143	128	89.5					1.246	1.209
45	32	.109	128	108	85.0	2.326	1.953	84	71.3	1.246	1.219

This table shows that the ampere hour and watt efficiencies decrease with increase of temperature, though the volt efficiency increases with the temperature.

The electrolyte density was taken by removing a small quantity from the cell, bringing to 18 degrees C. and testing with a hydrometer.

A noteworthy result of the change in capacity with heat is the apparent ability, by this means, to get more current out of a cell than is put in on charge. In the tests referred to, a cell was charged at 14 degrees C. with 61.9 ampere hours at a rate of .109 amperes per square inch. After being heated to 45 degrees C. the cell delivered on discharge 96 ampere hours. Charged at a rate of .0685 amperes per square inch, and at a temperature of

14 degrees C., 76 ampere hours were put into the cell and it discharged 108.3 ampere hours after being heated to 45 degrees C.

A further experiment was the charging and discharging of the cell at 14 degrees C. and allowing it to stand one and one-half hours. After recuperation, it delivered 8% more current. Under similar treatment in every respect, except that the cell was heated to 45 degrees C., while standing after the end of the first discharge, it delivered 33% more current after resting.

As explained in Chapter VIII, this energy of discharge in excess of that put into the cell on charge, comes from previous charges which have not been completely abstracted on previous discharges. Of course no greater amount of energy than that which has been stored in the cell, can be taken from it.

The explanation of these heat phenomena seems to lie in the increased porosity of the active material due to expansion under the action of heat, the increased circulation of the electrolyte, giving a more efficient use of the active material and the combining SO_4 and more active chemical combinations.

The fall of voltage on charge is due to increased diffusion, and reduction of resistance of the counter electro-motive force of polarization, by driving off the adherent and occluded gases. Possibly other causes may contribute to the voltage decrease.

The variations in capacity with temperature changes depend for their absolute values on the thickness of the layer of active material, its character and its disposition, and the discharge rate.

It is evident that the more porous the active material and the lower the discharge rate, the less will be the increase in capacity for higher temperatures.

A rough, handy rule that somewhat approximates the degree of change in capacity with change in temperature is:

At 6 hour rate, 1.5%
" 3 " " 2.5% } per degree centigrade
" 2 " " 3.2%

the capacity at 15.5 degrees being taken as unity.

The influence of heat up to 45 degrees C. seems to be in nowise detrimental to the plates used in these experiments nor to increase their depreciation. Heim suggests that if in practice and after prolonged usage at high temperatures it be demonstrated that within the limit of 45 degrees C. the durability is not impaired,

it would be good commercial practice to provide means for warming battery rooms up to this point so that the increased capacity gained thereby may be made useful in helping to carry abnormal loads that come on railway systems on holidays and special occasions which occur at such widely separated intervals that it would not be wise to invest in extra batteries or generating machinery to handle these sporadic overloads. It is, however, a well-known fact that excessive temperatures are injurious to batteries and tend to decrease their life. The temperature of 38 degrees C. seems to be about as high as batteries should be subjected to, according to the experience and statements of battery manufacturers.

The resistance of the electrolyte is subject to variation with temperature change, the temperature coefficient being negative, that is, with increase in temperature, the resistance decreases. Kohlrausch gives the following equation for the change in resistance with temperature:

$$R_T = R_{18} [1 - A (t - 18)]. \qquad 50$$

R_T is the resistance at the given temperature t, R_{18} is the resistance at the standard temperature of 18 degrees C., and A is a constant called the temperature coefficient.

TABLE XVII.

Per cent of H_2SO_4	Density	Res., Ohms per cu. cm. at 18° C.	Temp. Coefficient A.
15	1.1036	1.855	0.0136
20	1.1414	1.544	0.0145
25	1.1807	1.406	0.0154
30	1.2207	1.365	0.0162
35	1.2625	1.392	0.0170
40	1.3056	1.483	0.0178
45	1.3508	1.636	0.0186
50	1.3984	1.866	0.0193
55	1.4487	2.204	0.0201
60	1.5019	2.705	0.0213
65	1.5577	3.466	0.0230
70	1.6146	4.679	0.0256
75	1.6734	6.639	0.0291
80	1.7320	9.141	0.0349
82	1.7410	9.962	0.0365
84	1.7635	10.310	0.0369
86	1.7880	10.180	0.0357
88	1.7880	9.775	0.0339

The preceding table gives the density, resistance at 18 degrees C. and the coefficient A for different proportions of H_2SO_4 in the electrolyte. From these it will be seen that the greatest variation with temperature takes place with electrolytes carrying 80 to 87% of H_2SO_4. This is a matter of purely scientific interest, however, as no such densities are ever encountered in actual practice.

As may be seen from the foregoing formula, the resistance decreases an amount varying from 1.2% to 3.7% per degree C. increase in temperature, the amount of change depending on the concentration. Between the densities of 1.100 and 1.300, which are the practical limits for storage cells, the variation in resistance is from 1.36 to 1.78% per degree C.

In general, the effect of temperature increase is that the voltage is slightly augmented, by the amount $T \frac{dE}{dT}$, as set forth in Chapter IV. The resistance decreases, therefore the potential difference is augmented; the diffusion is also improved, so that the electrolyte is able to penetrate into the pores of the active material more rapidly and efficiently; and all of these factors tend to increase the output of a given cell.

Jumau has also shown that gases are liberated from the electrodes at lower voltages when the cell temperature is high than when it is low. His researches practically corroborate those of Heim.

On a certain cell he found that at 13 degrees C. the potential difference to produce gassing was 2.76 volts, while at 47 degrees the potential difference was 2.58 volts.

Laigre* conducted some experiments to determine the effect of temperature changes on a storage cell. These tests were made with plates of the Planté type immersed in electrolyte of 1.225 specific gravity. From his observations Laigre deduced a formula showing the capacity of a cell at any temperature, if its capacity at some other temperature be known, which formula is:

$$C_T = C_0 + 0.77\,t. \qquad 51$$

C_T is the capacity at any temperature, C_0 the capacity at zero degrees C., while t is the temperature to which the cell has been raised. This formula only holds between temperatures of zero

* Eclairage Electrique, Vol. XXIX, Nov. 2, 1901, page 149.

and 35 degrees C., and is at best only an approximation. Obviously, the real cause of the increase in capacity with augmented temperature lies in the more rapid rate of diffusion; and this rate of increase, therefore, must depend very greatly on the character of the electrodes and the disposition of the active material upon them. The capacity increase with temperature is far greater in the case of rapid discharge than with low discharge rates, as would

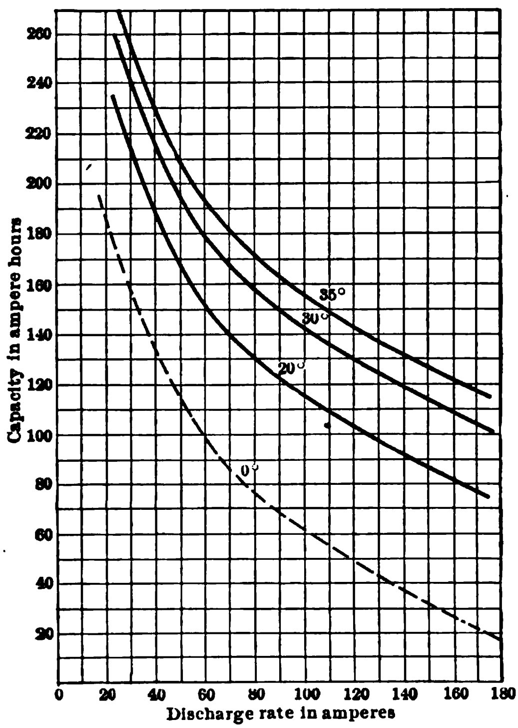


FIG. 53. Variation in Capacity with Temperature at Various Rates.

readily be anticipated. At low rates of discharge the natural diffusion at moderate temperatures is sufficient to supply the needed H_2SO_4 to the active material which lies beneath the surface of the electrodes; while in the case of rapid discharge, the rate of diffusion is not sufficiently rapid to maintain the electro-motive force at its proper value, and the temperature increase, which acts mainly to raise the diffusion rate, has therefore a far greater effect on the capacity at high discharge rates. The increase in

capacity may vary from .5 to 4.5% per degree C. increase in temperature, or from .3 to 2.5% per degree F. At the eight-hour rate, as a rough approximation, the capacity increase may be taken as 1% per degree F., the capacity at 60 degrees F. being taken as the datum. Fig. 53 shows the variation in capacity with temperature at different rates of discharge and clearly illustrates the foregoing theory.

As has been mentioned in Chapter X, the local action increases rapidly with increase in temperature. This is due to the fact that all chemical reactions take place more energetically at high temperatures than at low ones, and also to the increased rate of diffusion. A formula for computing the change in rate of diffusion of electrolyte in the pores of the plates with change in temperature is:

$$D_T = D_{18}\,[1 + 0.024\,(t - 18)], \qquad 52$$

D_{18} being the coefficient at 18 degrees C., D_T the coefficient at t degrees C. From this equation it may be seen that the augmentation of diffusion rate is 2.4% per degree C.

The local action is increased with higher temperature because the resistance of the electrolyte, which forms a part of the path over which the internal discharge currents travel, is decreased with increasing temperature. At very low rates of discharge the capacity of a cell may actually be decreased by increase in temperature, because of the augmented local action. On the other hand, no increase in capacity can result from increase in temperature, as the rate of diffusion is rapid enough at normal temperatures for the cell to deliver its full output at low discharge rates.

Jumau made some experiments to determine the variation in capacity with change in temperature on positive plates of the pasted or Faure type. These plates were mounted between negative plates, the latter having a capacity far greater than that of the positive, so that when the couple thus formed was discharged down to a point of exhaustion there still remained ample reserve capacity in the negatives, practically the entire decrease in potential taking place in the positive element. The results of these tests are shown in Fig. 54. From these curves it is obvious that the higher the rate the less is the change in capacity per degree increase in temperature.

Similar tests were made with single negative plates with positives on either side, having capacities much greater than that of the negative plate, so that the change in capacity was practically all referred to the negative element. The results obtained from these tests are shown in Fig. 55. From these curves it may be seen that the higher the

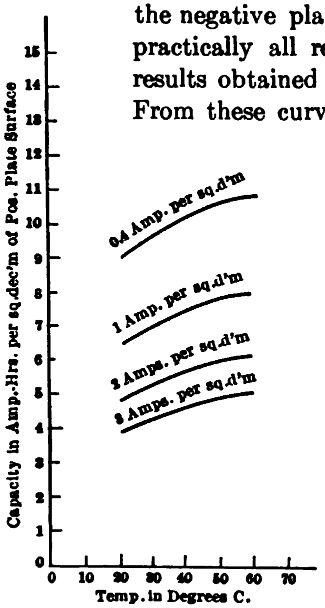


Fig. 54. Variation in Capacity of Positive Electrode with Temperature.

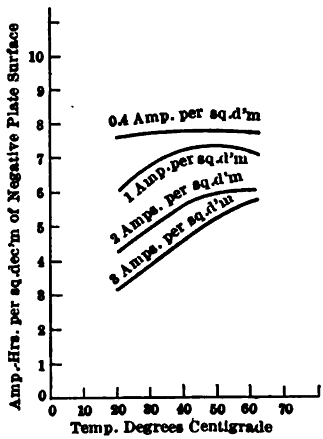


Fig. 55. Variation in Capacity of Negative Electrode with Temperature.

rate of discharge the greater is the increase in the capacity for a given increase in temperature of the cell. The combined effect of temperature change on both the positive and negative gives a greater increase of capacity per degree increase of temperature at high rates than at low rates. It will be observed in Fig. 55 that the curves have a tendency to bend at a point corresponding to about 43 degrees C., and from this point to droop downwards, showing that the greatest capacity of the negative plates is at about 43 degrees F., and above this temperature there is little or no capacity increase. This is probably due to the fact that at this temperature the rate of diffusion has become sufficiently high to be able to produce the full discharge of the cell, and the rapid local action begins to cause a decrease in capacity. Any further increase in temperature, therefore, cannot augment the capacity but will decrease it by an amount equal to the increase in the internal discharge. These curves are strictly applicable only to the particular type of plates used in these tests.

It is obvious that the increase in capacity with temperature is greater with thick than with thin plates, and also, there is a separate temperature coefficient for each type of plate, density of acid, and rate of discharge, and this coefficient is still further influenced by the porosity and the disposition of the active material on the electrodes. For this reason, pasted plates, in spite of their excessive thickness, frequently have a lower temperature coefficient than Planté plates with a thinner layer of active material, owing to the more porous nature of the active material on the pasted electrodes.

The ampere-hour efficiency of a cell decreases with increase in temperature, and this reduction is caused by the augmented local action. The watt-hour efficiency, however, is usually greater at moderately high than at low temperatures, because the charging voltage required is diminished and the potential of discharge is increased, and these two effects more than counterbalance the diminished ampere-hour efficiency. The increase, however, in watt-hour efficiency is slight, practically negligible, and at very low discharge rates the reduced ampere-hour efficiency may be the commanding factor and the watt-hour efficiency be actually lower with increased temperature, as was the case in the tests made by Heim and referred to in the first portion of this chapter.

A curious phenomenon, first observed and investigated by Duncan and Wiegand in America, and independently by Professor Ayrton, in England, is the decrease of temperature of a cell on discharge. This decrease may be explained by the fact that sulphuric acid is abstracted from water on discharge and therefore the liquid cools, this being merely the converse of the well-known fact that the addition of sulphuric acid and water is accompanied by the liberation of heat.

On charge the battery heats from two causes, one being the addition of SO_4 to the liquid, due to its electrolytic liberation from the $PbSO_4$. The other factor is the I^2R loss, which, however, is not a constant for any current, as R varies widely.

On discharge the abstraction of SO_4 from the electrolyte tends to cool the battery, the I^2R to heat it.

The actual temperature change will be that due to the difference between these two factors and up or down, according to whichever predominates.

Fig. 56 shows curves of temperature on charge and discharge and indicates the rise and fall of temperature with time.

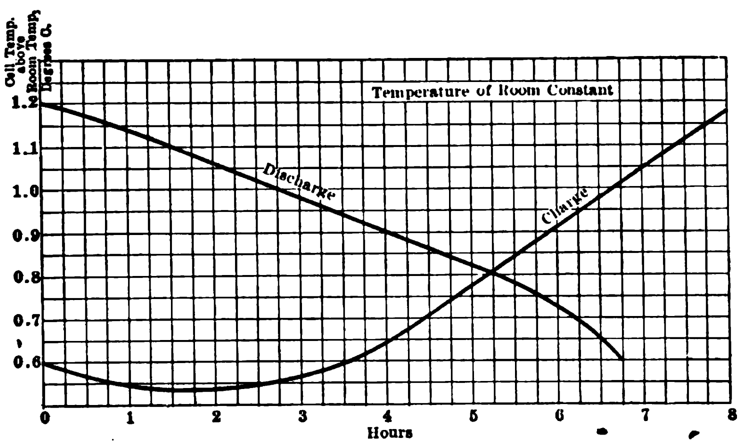


FIG. 56. Variation of Cell Temperature with Charge and Discharge.

CHAPTER XII.

EFFICIENCY.

THE efficiency of a battery is the ratio of the useful current or energy given out on discharge to that put into it on charge. The ampere-hour efficiency is the useful discharge in ampere hours, divided by the number of ampere hours input on charge, and the watt-hour efficiency is the ratio of watt hours output to watt hours input.

The work absorbed or given out by a battery is measured in watts, and only the energy or watt efficiency is of value to the engineer.

The efficiency of a battery depends on:

(1) The charging rate.

(2) The discharge rate.

(3) The virtual internal resistance.

(4) Thickness and porosity of active material.

(5) Density, quantity and diffusion of electrolyte.

(6) Length of time elapsing between end of discharge and beginning of next charge.

(7) Freedom from local action.

(8) Temperature.

The energy losses in a storage cell which tend to reduce its efficiency are (1) the I^2R, or resistance loss; (2) local action, or internal discharge; (3) evolution of gas at the end of discharge; (4) irreversible chemical reactions. The first of these obviously varies as the square of the charge and discharge currents and with the first power of the resistance. The second depends on the density of the electrolyte, its temperature, the impurities which may exist either in the active mass or in the electrolyte, and the length of time between the end of charge and beginning of discharge, during which the local action continues — in other words, the interval of repose.

It has been shown that the lower the rates of charge and discharge, the nearer the voltage curves approach together, and as

the difference between these two represents the pressure loss, it is obvious that the efficiency is higher at low rates of charge and discharge than at rapid rates. The virtual resistance tends to increase the voltage of charge and decrease that of discharge, causing a loss of energy. The efficiency is therefore largely dependent on the virtual internal resistance, though it is influenced also by certain chemical effects, especially gassing.

The thickness and porosity of the active material influence the values of the internal resistance and consequently the efficiency. Where the charging rate is rapid, the layer of active material thick, and diffusion imperfect, the voltage of the cell rapidly rises because of the high concentration of acid in the pores, which is unable to diffuse out into the surrounding electrolyte. This requires a higher charging voltage and the energy input is increased beyond the amount of actual energy stored. This lost energy appears as heat, and it will be found that batteries subjected to a high charging rate always heat up to a temperature above that due to mere internal resistance. The physical conception of the cause of the heat is the rapid concentration of H_2SO_4 which is always accompanied by the liberation of heat.

Certain secondary chemical reactions may also tend to increase the cell potential on charge and lower the efficiency.

On rapid discharge, polarization is increased, and assists in reducing the battery voltage. Also the extreme dilution of the acid in the pores of the plates — the converse of the effect noted on rapid charge — causes the potential to fall rapidly, and assists to end the discharge more quickly. As an example of variation in efficiency, with charge and discharge rates, the following results of a test by Dr. Franz Peters* are given:

TABLE XVIII.

Charging rate.		Discharge rate.		Amp. hr. effic. per cent.
Amps.	Amps. pr. sq. in.	Amps.	Amps. pr. sq. in.	
10	.121	9	.109	95.7
10	.121	6	.073	98.7
16	.1935	9	.109	80.8
16	.1935	6	.073	83.2

* Centralblatt für Accumulatoren, Jan. 15, 1901.

The watt-hour efficiencies are not given, but these would show a greater difference between moderate and rapid current rates than the above figures.

It is not to be supposed, however, that if a battery be charged and afterwards discharged at a rapid rate, the ratio of output to input is the true efficiency. Whenever the output is far less than the input just preceding, it will be found that the succeeding charge will be less than the previous one. Also the recuperative capacity of the battery is much greater than if the discharge had been normal. In other words, if a battery be discharged at a rapid rate, the available energy is not taken out of the cell by the time the voltage falls to 1.8, and there is a considerable residual charge left. Failure to appreciate this fact has frequently led to erroneous determination of battery efficiencies. Efficiencies should be calculated as the summation of a series of cycles of charge and discharge, all being at the same rate and under the same conditions.

The efficiency of a cell is difficult to fix exactly, as the amount of charge is indeterminate, therefore no single test is sufficient to determine the efficiency. That portion of the charge given to the cell when the charge is nearly completed and when gassing begins, may vary considerably, and for this reason the only figure that can be used as the energy input required to bring the cell up to full charge is the average of a number of, say not less than seven, separate charges, each taking place after a discharge, which discharges are all at the same rate and stopped when the same final voltage has been reached. It is also necessary that several charges and discharges be taken before efficiency tests are made, because the influence of previous charges and discharges may greatly influence the records, and in some cases produce an efficiency of over 100%. Thus, if a cell has been fully charged at a low rate, then discharged at a rapid rate, and discharge cut off at a given cell potential, say 1.8 volts, and a subsequent charge be given immediately thereafter, it is obvious that the energy input required to fully recharge the cell is not as great as would have been required if it had previously been discharged at a low rate and a greater amount of energy abstracted from it. If, subsequent to this second charge, a discharge be taken at a low rate, a greater amount of energy may be obtained from the cell than was actually put into it on the immediately preceding

discharge, and the ratio of the input to the output may show an efficiency of considerably over 100%. As a matter of fact, the energy taken from the cell would come not only from that given to it on the immediately preceding charge, but also from the partial charge that the cell possessed as a result of having passed through the prior cycle of charge and discharge in which all the available energy was not taken from it. Also in order to obtain a true record of the efficiency, the temperature must be maintained constant throughout a test. It is possible to charge a cell at one temperature, bring it to a higher temperature, and then discharge it, and on the discharge obtain an output greater than the preceding input. This excess energy of course comes from that which had accumulated from previous charges, and which lies dormant in every cell until its activity is increased by reason of more rapid diffusion and more energetic chemical action, both of which obtain at higher temperatures.

The efficiency is also somewhat dependent on the acid density, as the resistance of the electrolyte varies with the percentage of H_2SO_4 in the mixture; and the lower the resistance of the electrolyte the higher will the efficiency be. This statement applies only to cells which are fully charged and subsequently fully discharged. Where cells are used for regulation of load and subject to high rates of charge and discharge for very short intervals of time, this statement does not hold.

If a cell which has been rapidly discharged, be allowed to stand for a considerable time, the residual charge will be partly lost by the absorption of some hydrogen, and the ineffective combination of the PbO with the SO_4. Therefore, the efficiency is higher if the charge and discharge succeed each other rapidly. This is the condition under which regulating batteries operate which equalize fluctuating loads. They also have the advantage of charging and discharging at a point where the charging voltage is below the gassing point, and the discharge potential is near its highest value.

If current be alternately taken out of and put into the cell at short intervals, the *quantity* of charge will not be materially altered, even though the *rate* may be rapid, because the *time* of charge or discharge is short. Therefore the point on the voltage curves of charge and discharge at which current is put into or drawn from the battery will shift but little.

Both B. Hopkinson* and Jumau investigated the action of cells on high charge and discharge rates lasting for brief periods of time and following each other in rapid succession.

Fig. 57 shows the results of one series of Hopkinson's tests and these are characteristic of all his investigations on this subject.

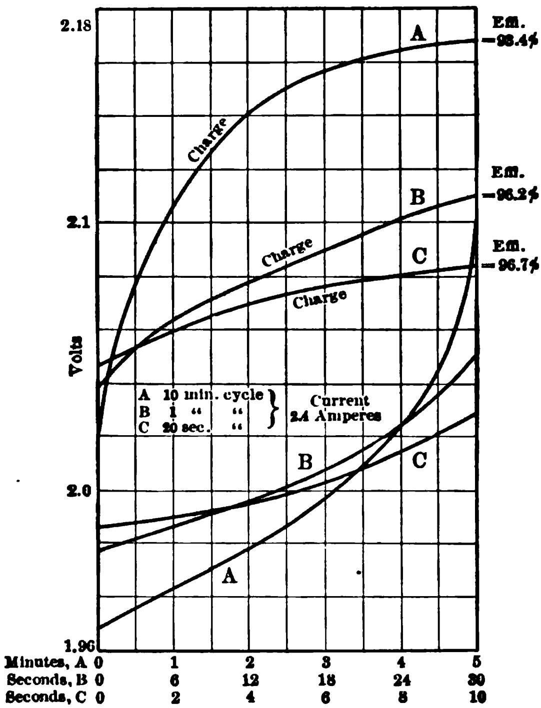


FIG. 57. Charge and Discharge Curves for Short Periods.

Curves A are charge and discharge curves for a discharge of 5-minutes duration and a charge for an equal length of time; B is for a 30-second, while C is for a 10-second charge and discharge, the discharge curves being plotted in a direction reversed to that of the curves of charge for better comparison between the two sets of curves. The energy loss is practically equal to the area included between the pair of curves, similarly lettered, which refer to the test under consideration. As is clear, the shorter the time of discharge the less is the loss per unit of time and the higher the efficiency of the cell.

* Electrician (London), Vol. XLVIII, Nov. 29 and Dec. 6, 1901.

The efficiencies as computed from the curves are

Curve A, 93.4%; curve B, 96.2%; curve C, 96.7%.

From which it appears that the shorter the cycle of charge and discharge, the higher is the efficiency; and in the case of regulating batteries in which the length of a cycle seldom exceeds one minute, an efficiency of 90% or more may be counted on.

Jumau* in somewhat similar experiments found the efficiency to vary from 93 to 96%, thus corroborating the conclusions reached by Hopkinson. The reason for these high efficiencies for brief periods of charge and discharge lies in the fact that there is practically no change in concentration of the electrolyte in the interior of the active mass, and the only factors which act to cause a loss of energy between input and output are internal resistance and local action. Therefore the efficiency of cells on quick charges and discharges does not change with changes in acid density, and Jumau's experiments have shown conclusively that this is true in practice.

As has been pointed out in Chapter XI, the watt-hour efficiency changes but little with the temperature; the ampere-hour efficiency is reduced, but the voltage loss is also diminished, and the product of the higher pressure and the lower ampere hours is practically the same throughout ordinary temperature ranges. The general tendency is to slightly raise the efficiency with increase in temperature, except for low current rates of discharge.

It may be mentioned here that batteries other than lead cells, and which have a low voltage, say from .75 to 1.3 volts, can never have a very high efficiency, however well they may perform their work. The reason lies in the fact that the lower the voltage of a cell, the greater is the ratio of internal resistance and polarization drop to the cell voltage, and, consequently, the drop is a large proportion of the cell electro-motive force. Therefore, while such batteries may be useful for conditions where current cost is a secondary consideration — such as motor car work — they would hardly pay dividends in a central station where a difference of a few per cent in efficiency is often the determining factor in the selection of any apparatus.

The density, quantity and diffusion of the electrolyte all have a marked effect on the efficiency of a cell. The density must be

* Les Accumulateurs Electriques, page 362.

such that the resistance of the electrolyte is low; the quantity must be sufficient to prevent a great change in density on discharge, and the voltage is largely dependent on the rate of diffusion.

If the diffusion is poor, the electrolyte in the pores of the plates will be subject to great concentration on charge and dilution on discharge, with a correspondingly augmented voltage in the one case, and diminished in the order. Therefore, if the quantity, density and rate of diffusion of electrolyte are of proper value, the result will be a low voltage on charge (up to the point of gassing), and a high voltage on discharge, and if a cell be deficient in these particulars the increase of the one and the lowering of the other will cause a loss of energy and a decrease of efficiency.

If a cell be allowed to stand discharged, sulphation proceeds, and on subsequent charge a greater number of ampere hours at a higher voltage must be put into the cell to bring it up to full charge than would be required if the charge had been begun immediately after ending the discharge. The excess energy necessary to fully charge the cell represents a corresponding loss in efficiency. If internal discharge takes place, the amount of energy so used up is lost, as it does no useful work, and therefore the efficiency is decreased. Furthermore the positive plates or grids are unnecessarily corroded.

Under usual conditions, the watt efficiency of a battery used for storage only — that is fully charged and subsequently fully discharged — is from 70 to 80 per cent. The larger the battery, and the higher the voltage at the end of discharge, the greater will be the efficiency. With large batteries, in which the charge is never continued very long after gassing begins and discharge is stopped at about 1.87, the efficiency of storage cells may be as high as 85%. A fair commercial figure is 80% for storage, and 92% for regulation batteries.

Methods for determining efficiency are given in the chapter on Testing.

CHAPTER XIII.

TYPES OF PLANTÉ PLATES.

THE Planté process derives its name from Gaston Planté, who, in 1860, first produced a practical storage cell by passing current between two lead plates immersed in dilute sulphuric acid. After the expiration of a short time, a slight coating of peroxide of lead was formed at the anode, the cathode being unchanged. On reversal of direction of current flow, the peroxide was reduced to metallic sponge-lead by the hydrogen — the peroxide element having become the cathode — and the previously unattacked plate was peroxidized. This, then, constituted a storage battery, but of negligible capacity, as the layers of active material were infinitesimally thin, owing to the fact that the action of the oxygen on the lead can penetrate no further after a layer of peroxide has been formed.

By repeatedly reversing, Planté was able to increase the depth of the coating of active material sufficiently to produce a storage cell that compares favorably with any cell made to-day. It required, however, several months to do this, and was very wasteful of electrical energy. Therefore the process is not a practical commercial one, but based on Planté's original work, accelerated processes have been developed. All processes which produce active material upon the plate, and out of the base lead of which it is made, are now termed Planté processes.

Since the layer of active material formed from the surface of a lead sheet is very thin, it is necessary to provide a large surface in order to form an appreciable volume of it. An ordinary sheet of lead subjected to a "forming" process would have so small an amount of active material produced on it that the resulting electrode would have but little capacity.

For this reason, and also to provide secure lodgment for the active material, it is customary to make electrodes with grooves, ribs, laminations or other surfaces which present a greatly increased area to the action of the "forming" process for a given size of plate.

The PbO_2 formed on such plates is mechanically held in the interstices. With positive plates, it is advisable to retain the active material between ribs or in pockets, as it sheds rapidly from exposed surfaces.

Manufacturers frequently claim that the area of a ribbed or grooved plate is many times greater than the product of the length by the breadth. This is true only when the plate is unformed, and before it is ready for service. After formation the spaces between the ribs or laminæ are practically filled up with active material, so that the area exposed to the electrolyte is substantially the same as that of the planar surface.

The various methods of subdividing the surfaces of the lead plates to give a large area for the formation of active material are: *Scoring; swedging; grooving; laminating; casting.*

Scoring consists in passing scoring wheels over the lead sheet. The sheet is passed slowly between two opposite sets of wheels which are very thin and are slightly beveled from the periphery towards the center. They are run in gangs of 200 to 400 wheels on the same axle, the number varying with the width of the plate. Where the edges of the wheel rims enter the lead, grooves are left, and between the wheel tracks the soft lead is forced up in the form of thin ribs or leaves, and raised above the surface of the original lead blank. As a result of this compression, the lead of the ribs is very dense and tough. By making the ribs very thin, thereby getting a great number in a given size plate, a large area is produced.

Figures 58 and 59 show the Gould Storage Battery Company's plate, which is made in this manner, Fig. 59 being a section. The effective area is twenty times the original area of the plate, when the grooving is very fine. The thinnest ribs are .012 inch thick, while the heaviest grooving produces ribs .042 inch in thickness. The grooving is varied between these limits, the thickness of the ribs being made to suit the conditions under which the battery is to operate.

Plates so made have the advantage of being a single integral mass, without joint or contact, and of allowing expansion to a reasonable extent. The web which is left in the center of the plate forms the grid, and gives conductivity.

The raising of the ribs above the surface of the plate, so that the thickness of the grooved element is greater than that of the

original sheet, is clearly shown in Fig. 59. It is also to be noted that the entire surface of the plate is not grooved. Reinforcing ribs of the solid lead are left at intervals, as shown in the figures.



FIG. 58. "Gould" Plate.

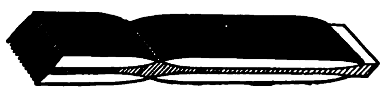


FIG. 59. Sectional View of "Gould" Plate.

Swedging. An example of a plate made by the swedging process is the "National" plate. The swedging means consist of a number of cutting segments of sheet steel placed side by side on a shaft. These segments turn through a small angle, moving only partly around the axle and then turning back in the opposite direction — a sort of forward and back movement. The segments are gradually fed deeper into the plate, this movement continuing until the required depth of groove is obtained. As in the case where wheels are used, the lead ribs formed between adjacent segments are squeezed up above the plane of the original plate surface.

The cutter segments are beveled from the thin edge of the periphery to about ½ inch from the edge and therefore cause the ribs to take a similarly beveled form. The gradual feeding in of the beveled segments compresses the lead ribs as they are squeezed up above the surface of the plate, thereby causing them to become very dense and tough.

At proper intervals, nicks or grooves are cut in the periphery of the segments so that strengthening ribs of ungrooved metal are left, transverse to the direction of the fine, scored ribs.

Fig. 60 shows a plate made by this process before forming, while Fig. 61 shows the plate after formation. Cross and transverse sections of an unformed plate are shown in Fig. 61a.



FIG. 60. "National" Plate (Unformed).

Grooving. There are two methods of grooving. In one the ribs are sliced out from the lead sheet by a tool on a shaper which moves back and forth, while at each forward stroke the plate advances transversely to the path of the tool just the thickness of one rib. The tool therefore slices out one complete rib with each stroke.

The cutting edge is set at an angle with the plate surface, so that the ribs stand out at an angle with the surface, the inclination being upward from the central web. It is intended that the grooves will form pockets to hold the active material and prevent it from dropping off from the plates.

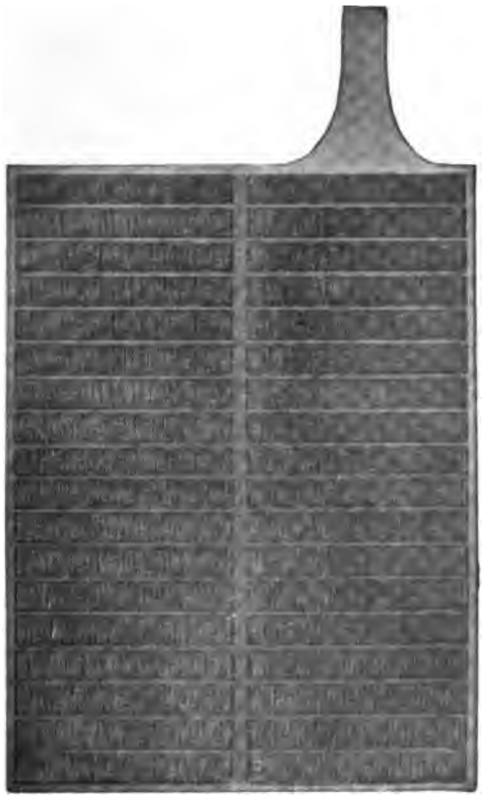


FIG. 61. "National" Plate (Formed).

Figures 62 and 63 show respectively the Willard cell and cross section of plate, made by this method.

Another form of grooving is by sawing out the slots and leaving a ribbed plate. This is, however, not much used.

Laminating consists in making up a plate of lead ribbon, the width of which is equal to the thickness of the plate, or by mechanical means reducing a lead sheet to a series of laminæ.

An example of the former type made in America is the "Manchester" plate of the Electric Storage Battery Company, and shown in Fig. 64.

This is made by passing lead ribbon between a pair of rollers, one of which is toothed. This produces a series of ridges or "crinkles"

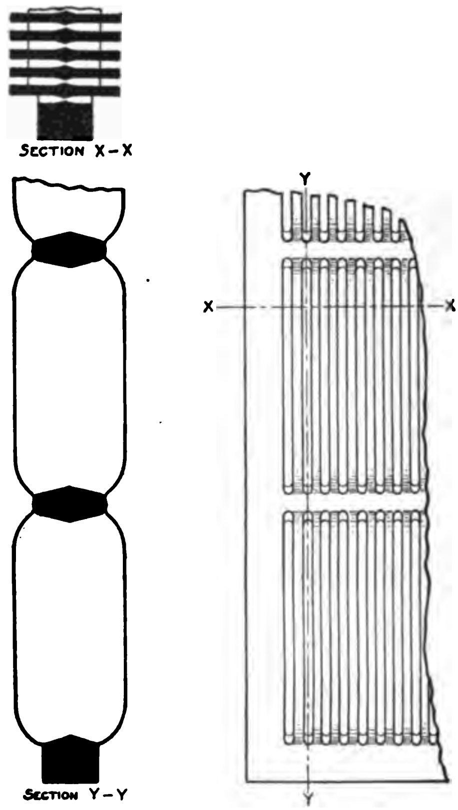


FIG. 61a. New Sections of "National" Plate.

on one side of the ribbon, the other side remaining smooth. "Buttons" or plugs are formed by rolling up a short length of the ribbon in a close spiral. These are pushed into circular holes which are cast in the supporting grid — this latter being a lead-antimony alloy. The ridges, previously formed on one side of the ribbon, make a series of fine passages through from edge to edge of the button, which give a considerable area for formation of

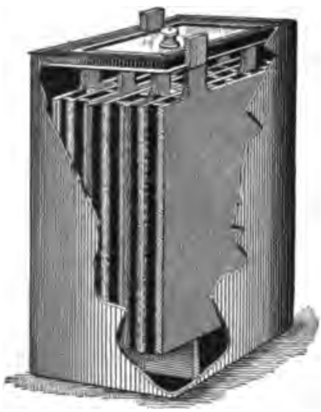


FIG. 62. Willard Cell showing Plates.

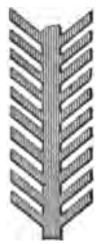


FIG. 63. Cross Section of Willard Plate.

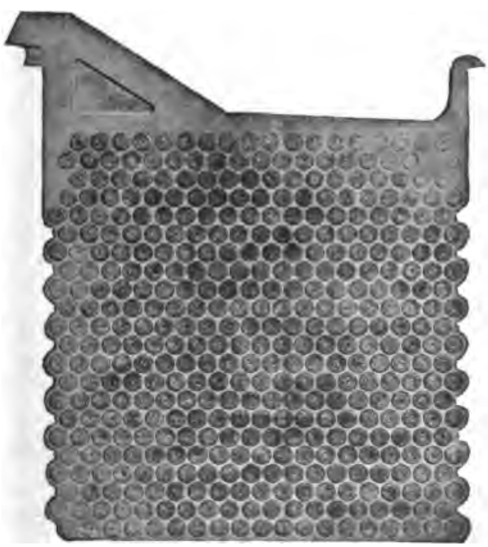


Fig. 64. Manchester Plate.

active material. When the plates are formed, the plugs expand and make firm contact between the plugs and the grid.

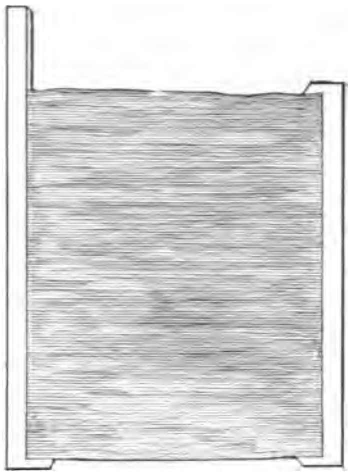


FIG. 65. Dujardin-Planté Plate.

The D. P. Battery, made in England by Drake & Gorham, is shown in Fig. 65. The laminæ are straight, and their ends are connected by casting a lead bar or rib on each side of the plate as indicated. It is to be noted that the side bars are not held together at the top and bottom by cross bars. This construction allows the plate to expand freely with discharge and to contract on charge.

The Westinghouse plate, shown in Figs. 66 and 67, is an example of a laminated electrode in which the strips are formed by mechanical cutting through of the lead sheet. Fig. 66 shows the plate just after lamination and before

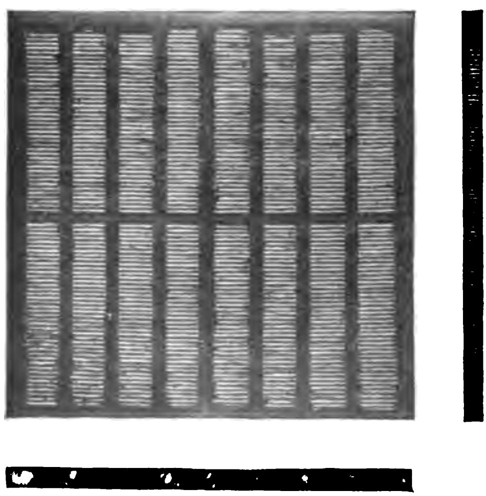


FIG. 66. Westinghouse Plate (Unformed).

it has been formed. Fig. 67 is a picture of the electrode after formation. As will be observed, cross ribs and reinforcing longi-

tudinal rods are formed by reducing the depth of the cut at equidistant points along the length of the laminæ.

The Blot electrode is made up of laminations fashioned into long hanks. The laminations are alternately flat and corrugated, and all knurled.

The length of a hank is twice the length of the plate into which it is to go, and about 1¾ inches wide. The thickness of

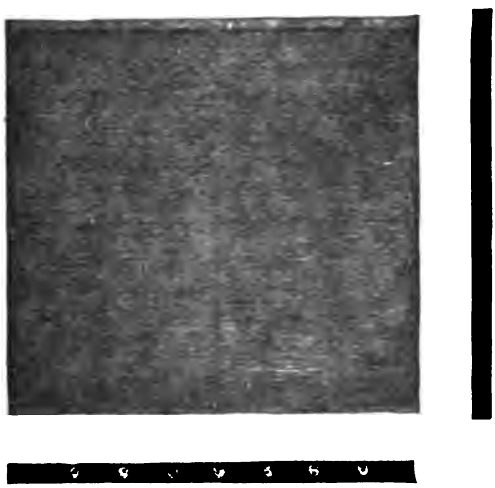


FIG. 67. Westinghouse Plate (Formed).

the plate, corresponding to the width of the lead ribbon forming the hanks, is ⅜ inch. The thickness of the lead ribbon is ½ m/m.

The hanks are wound about two narrow forked pieces at either end, these latter being made of lead-antimony alloy. When finished, the hanks are cut in two across the middle. The plate is made up by joining these half hanks to the upper bar of the plates, the end carrying the forked piece being fastened to the bar by soldering or burning the latter onto it. The laminæ are also joined at the same end by welding them together solidly. The lower ends hang free and are prevented from moving sideways out of the plane of the plate by cross bars on each side. This does not interfere with the longitudinal expansion of the hanks. Fig. 68 shows an electrode made in this manner.

Casting. By cutting molds in steel or brass and injecting cast lead under heavy pressure, nearly any form of electrode can be produced.

Usually the pressure is applied by means of a piston working in a cylinder, the latter having a valve at the bottom made of a steel ball lying in a properly fitted seat. Attached to the piston is a long lever handle by means of which the piston is moved. An iron pipe leads from the bottom of the cylinder to the mold. There is no valve in this pipe opening. The pump is placed inside the melting pot so that it is surrounded by molten lead. On lifting the piston the lead runs in at the bottom opening of the cylinder, and on bringing down the piston the lead imprisoned by the ball valve is forced into the mold.

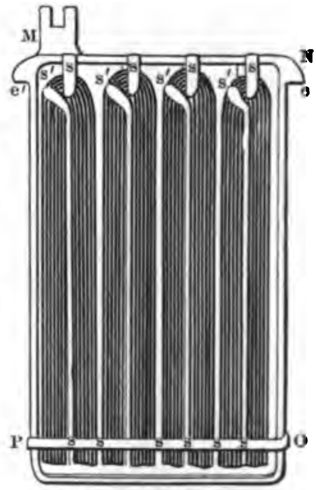


FIG. 68. Blot Plate.


FIG. 69. Bijur Plate (Formed).

The Bijur plate, shown in Fig. 69, is an example of a laminated plate made by casting. The separate sections are cast, and after being laid in a second mold in their proper relative positions, the holding frame, which is a lead-antimony alloy, is cast around them, thus producing the complete electrode as depicted in the cut.

By an ingenious process, the casting of the frame is accompanied by a complete welding of the leaden "grills" or laminated sections with the frame at every point where the two make contact with each other. The reinforcing cross ribs in the grills are clearly seen in the picture.

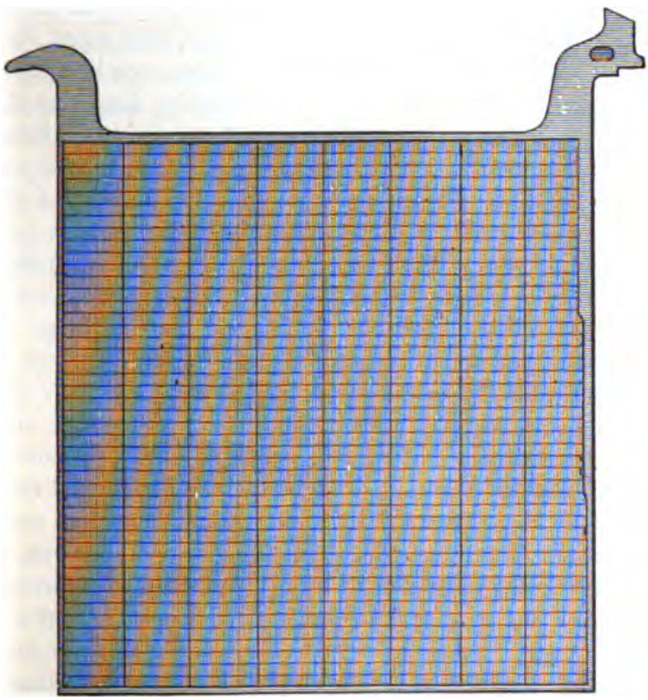


FIG. 70. Tudor Positive Plate.

Another form of cast plate which has proven successful in Europe and lately in use in America is the Tudor plate shown in Figs. 70 and 70a, the latter being a sectional view of the positive plate.

As indicated, the plate is one solid casting without any special provision for expansion. The ribs run through from face to face thus allowing free circulation of the electrolyte through the plate.

In making up plates for formation, much careful experimenting must be done to find just how far the plate may be subdivided for a given character of service. With positive plates, too many ribs or laminæ will allow the formation of more oxide than the plate can carry, and result in "buckling," or forcing out in the form of shallow pockets, certain portions of the plate. When the plate has expanded to its limit, and more material still forms in the plate, expansion must take place in a direction perpendicular to the plane of the plate, thereby distorting it.

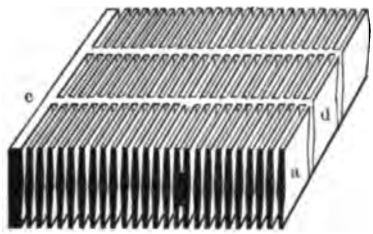


FIG. 70a. Section of Tudor Plate.

On the other hand, if the plate be not subdivided sufficiently, the area exposed will be small, and the capacity of the plate correspondingly limited. There is some particular number of ribs or laminæ in each type of plate that gives the greatest possible capacity, within the limit of buckling or distortion. The depth of the layer of peroxide is a function both of expansion and plate capacity, and the number of subdivisions may be large with a thin formation, or small with a thick formation. It is in many respects desirable to have the formation as thin as practicable, and a large number of laminæ. A thin layer of active material gives a more uniform voltage on discharge, admits of more rapid charge and discharge, and for batteries where the current rates are high, the thin layer is especially applicable. The active material, however, expands and contracts with discharge and charge, and a thin layer, offering a greater surface, must undergo a correspondingly greater degree of expansion and contraction than a thick formation, and therefore is more liable to peel off from the supporting ribs. From this, it follows that batteries which are to be charged to their fullest capacity and then discharged continuously to the minimum voltage, should be thickly formed.

On account of its crystalline nature lead, when stretched, has pores opened in its surface into which corrosion may sink rapidly. This is shown by the fact that the lead ribs or similar members on the convex side of buckled plates are corroded much more rapidly than on the concave or unstretched side. It is apparently true that plates having grooves or interstices filled with active

material are subject to corrosion to a lesser extent than those where the grooves are empty, the latter plates depending on the superficial layer of active material entirely for their capacity. With filled grooves, the active material seems to serve as a protective coating, retarding corrosion.

The growth and buckling of plates is apparently a maximum with open grooved plates as distinguished from those having grooves which are filled. The growth of soft lead plates appears to be always a maximum in a direction corresponding to the length direction of the ribs. The growth in the cross direction is very small under normal conditions but may become serious if the plates are allowed to become sulphated or there is an abnormal corrosion of lead underlying the active material. The small cross sectional growth is explained by the fact that the porosity of the active material allows room to take up a further amount in the grooves. The greater longitudinal growth is due to the fact that lead peroxide has a greater volume than the lead from which it is formed and there is considerable cohesion between the two: this results in a stretch in the length direction of the rib.

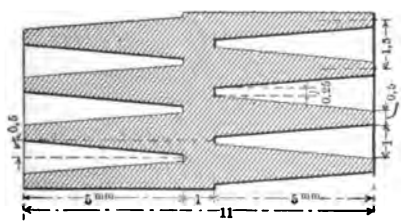


FIG. 71. Section of Planté Plate.

Fig. 71 shows the cross section (enlarged) of a cast ribbed electrode with all dimensions of ribs, spaces and web. These proportions have been found to be a good compromise between the various conflicting factors of plate design.

As the lead portions of the electrodes subjected to formation expand greatly, or "grow," it is necessary to provide for this expansion in some manner as in the cases of the "National," Blot and other electrodes hereinbefore described. In the case of solid plates made from a single sheet of lead, the formation must be done carefully, so that the spaces between the ribs are just filled with active material. The ductility of the central web allows

it to distend somewhat to accompany the increase in length of the ribs; that is, if the dimensions of the plate be not too great. In the case of the " Manchester " positive plate, the plugs are pushed lightly into the holes of the supporting grid and the expansion on formation becomes useful in causing the plugs to tighten in place.

The Westinghouse electrode, in the larger sizes, is made up as shown in Fig. 72 of a series of sections as indicated. The spaces



Fig. 72. Large Westinghouse Plate.

between the laminations admit of lateral expansion. To allow expansion in the direction of the length of the ribs, rectangular openings 0, 0, 0 are cut in the plate at the corners of each section. The sections vertically adjacent are joined together by a transverse lead member M, the cross section of which is S-shaped. This cross rib, being unattached to the vertical ribs, is free to bend and thereby take up any change in the length of ribs of the sections.

The large size National plates are made as shown in Fig. 73 and are also made up of small sections or units. These are welded at their upper edges to the supporting grid and small clips or projections are fastened to the frame near the lower edge of the opening

in which the unit electrodes are fastened. These clips prevent any lateral motion of the units and cause them to remain in the plane of the plate. The supporting grid is a casting of lead and antimony alloy.

Since the openings in the supporting grid are larger than the electrodes placed therein, and these latter are fastened on one side only, they can expand in every direction.



FIG. 73. National "Unit" Plate.

The Bijur plate is also a "unit" electrode, being made up as described previously in this chapter and shown in Fig. 69. As will be observed, the units are made up of a number of laminations braced by transverse ribs at frequent intervals. The sections are held in place by being welded to the supporting frame at several points on the sides of the grills.

These supporting points are located halfway between the transverse reinforcing ribs of the grills. Therefore, as these reinforcing ribs lengthen under the process of formation, the outer laminations

at each side of the grills simply bend slightly between the points of support. The grills being smaller than the openings in which they are placed, there is room for both longitudinal and transverse distention.

The foregoing are only a few of the most important methods of making up plates for Planté formation, but illustrate practically all of the types.

For more extended data and descriptions of these and other forms of plates, no better references are to be had than the trade literature of the various storage battery manufacturers throughout America and Europe.

CHAPTER XIV.

METHODS OF PLANTÉ FORMATION.

In the methods of formation to be described, the lead is attacked and finally converted into lead peroxide, probably passing through intermediate stages. After being fully formed as positive plates, all that are intended for negatives are reversed, the peroxides being changed into sponge-lead.

Sheldon and Waterman have shown, by a very interesting experiment,* that as the Planté process of formation proceeds in sulphuric acid, the lead is first changed into lead sulphate, and afterwards into lead peroxide, an appreciable time element elapsing between the first and second stages.

The experiment consisted in passing alternating current of various frequencies through two electrodes immersed in dilute sulphuric acid, and noting the frequency and resulting deposit. At low frequencies the deposit was brown peroxide, and at high frequencies, white sulphate only was produced, which fell from the plates as fast as formed. In the former case, the time of one impulse was long enough to form sulphate and change it into peroxide; in the latter, the impulse lasted only long enough to form the sulphate, which was thrown off on the succeeding impulse in the opposite direction.

The methods of rapid or autogenous Planté formation may be classified as *chemical*, *electro-chemical*, *electrolytic* and *amalgamating*.

The electro-chemical may be subdivided into three groups:

The first group is that in which one of the acids which dissolve lead, or a salt, the acid of which belongs to the lead dissolving class, is used in combination with some sulphate or carbonate.

The principal acids which dissolve lead are hydrochloric, nitric

* The Formation of Lead Sulphate in Alternating Current Electrolysis with Lead Electrodes. Samuel Sheldon and Marcus B. Waterman, Physical Review, No. 22, Vol. IV (Jan.–Feb. 1897).

and acetic. When these lead solvents are used, there must also be present a carbonate or sulphate, to act as a re-depositor of the lead which is dissolved by the acid. There can be many combinations of lead dissolving acids with carbonates and sulphates, a mixture of any of these being substantially the same in its effects. The difficulty with this character of formation is to rid the formed plate of the last traces of the acids which attack the lead. Unless these acids are completely removed, the forming process will continue during the use of the plate, with the result that the plate is soon eaten away.

The second group of electro-chemical formation is an accelerated Planté process, in which the necessity of repeatedly reversing the current through the plates is obviated.

This group is based on the theory that two peroxides which are present in the same solution tend to discharge each other. Therefore, if a formation proceeds in dilute sulphuric acid to which some peroxide has been added, the lead peroxide which forms on the surface of the plate, by reason of the electrolytic action, is deoxidized by the peroxide which has been added to the electrolyte. This deoxidation takes place almost simultaneously with the primary oxidation, which is practically equivalent to the continuous formation of lead sponge. The formation is therefore continuous, and does not require reversals of current.

The third group comprises the miscellaneous electro-chemical formations not included in either the first or second group.

In processes to be hereafter mentioned there are, in many instances, specified proportions given of the chemicals which are used to make up the electrolyte. In very few instances, however, will these proportions be found correct, as the inventors usually specify wrong proportions to mislead competitors, and only reveal the chemicals used, there being nothing further than this required to protect their processes. For this reason, the proper proportions will generally have to be found by experiment.

The forming baths may be acid, alkaline or neutral, according to the character of the sulphate or carbonate used and the proportion thereof used in the solution.

If the electrolyte be extremely dilute, PbO_2 is not produced, but a lead hydrate is formed which detaches from the electrode and floats on the surface of the liquid.

When formation takes place in neutral solutions, an important

superoxide hydrate of lead is formed, which gives great hardness to the active material. Additions, like mercury sulphate, favor the formation of proportionately harder superoxides, probably through the retardation of the changes in the sulphuric acid by the mercury salt.

As a general rule, the higher the temperature of the electrolyte the less fast to the supporting conductor and the less hard is the resulting superoxide deposit. This also becomes more brittle and harder the lower the current density, other conditions being the same. The temperature of the bath should never exceed 90 degrees F.

Of the various processes, the electro-chemical seems to offer the best method for producing a durable plate, of high capacity and efficiency.

CHEMICAL PROCESSES.

Chemical processes of formation are practically obsolete. In general, the treatment of plates comprises the chemical corrosion of the lead to form lead hydrates, carbonates, or oxides, and subsequent electrolytic oxidization of the corroded material to PbO_2 or its reduction to sponge lead, in an electrolyte of dilute sulphuric acid.

An example which illustrates this process is that in which a porous layer is produced on the surface of the lead plate by the action of dilute nitric acid. The acid should be very weak, usually about 1% of the mixture, the specific gravity at 60 degrees F. being from 1.005 to 1.006. About one quart of the fluid to every square foot of the lead surface is required. The plates are immersed in some vessel which will not be attacked by the acid, such as salt glazed stone ware, and the temperature is then raised to the boiling point of the liquid. This is maintained for a period of about twelve hours. The plates are then removed and exposed to the air, and after that again immersed and boiled for a short period, about seven hours. After removing the second time, the plates are washed with hot water, and afterwards in very dilute sulphuric acid. They are then formed in fresh sulphuric acid electrolyte, of specific gravity of about 1.15. The electrolyte in which the plates are formed should never be used when the plates are put into practical operation.

The objection to this process is that it is very difficult to remove the last traces of the nitric acid, and if any of it remains the active material is caused to flake off from the conducting support, due to the corrosion of the underlying metal.

ELECTRO-CHEMICAL PROCESSES.

The electro-chemical processes of Planté formation are now used almost universally. They are all based on the following general conditions.

The plates to be formed are first carefully cleaned — usually by chemical "pickling." They are then immersed in a forming bath of dilute sulphuric acid containing a small amount of some lead dissolving acid, or a salt of such acid. The plates are then connected as anodes and a current is passed through them, plain lead sheets — called "dummy" plates — being used as cathodes. The current density employed must be low enough to preclude the possibility of gassing and to produce a corrosion of the plates; that is, it must be such that the potential difference between the plates and the electrolyte is below the critical difference of potential as set forth in Chapter III. This potential difference, and therefore the current density, depend on the concentration of the electrolyte, the temperature and the proportion of the lead attacking acid in the electrolyte. The structure of the resulting active material can be greatly varied by a proper choice of these factors.

After the low current density has corroded the plate sufficiently, the rate is increased and the corroded material completely converted to lead peroxide.

The lead corroding acids or salts simply accelerate the process by allowing a higher current density and therefore a more rapid rate of corrosion, than if the electrolyte contained only sulphuric acid.

The acids generally used are nitric or perchloric, though acetic, hydrochloric, tannic and other organic acids may be used.

As per-chloric acid is explosive and some of the others are difficult to handle, it is customary to use salts of these acids instead of the acids themselves.

An example of the electro-chemical process is that of Du Jardin.

In this method an electrolyte is used of dilute sulphuric acid one-half saturated with sodium nitrate (Boettcher recommends the addition of a small amount of acetic acid to the solution). The proportions given are: 1 part sodium (or any alkaline) nitrate; 2 parts sulphuric acid; 10 parts water; proportions all by weight. The solution really becomes one of an alkaline sulphate with free nitric and sulphuric acids, so that the formation is practically one in nitric and sulphuric acids. The nitric acid which is formed becomes deoxidized, but it can be regenerated by forcing air into the bath.

The texture and porosity of the lead peroxide is influenced by the addition of certain inert salts, such as magnesium sulphate, potassium sulphate and the like. Schoop has suggested the following process. The bath of 5 kilograms sodium bisulphate; 100 grams potassium chlorate; 45 liters of water. Current is passed through at the rate of 0.4 of an ampere per square decimeter of anode surface. After removing from the forming bath, the plates are put into sulphuric acid electrolyte of specific gravity of 1.100, and the current passed through in a direction opposite to that used in the first bath, the PbO_2 previously formed being reduced to lead sponge. Dummy plates are used for the opposite poles. This second step is for the purpose of removing the chlorine, and the electrolysis is finished when the brown plates become thoroughly reduced to sponge lead. These plates are then removed, washed well in water, and dried in air. They are afterwards further completely dried at a temperature of 200 degrees C. This converts the sponge lead to a lead sub-oxide. This is afterwards converted to peroxide in an electrolyte of 25% sulphuric acid, the current density being one ampere per square decimeter. The uniformity of the layer formed is increased by blowing air into the liquid. The temperature should be maintained between 25 degrees and 35 degrees C. Time of formation about one hundred hours.

Similar results were obtained with the same mixture, more dilute, using about twice the amount of water. The time required in the latter case, however, is about two hundred hours.

The sodium bisulphate in the first forming bath can be replaced by sodium sulphate (Glauber's salts) with the same relative concentration. The results, however, are not so good in the latter case.

Two interesting processes are the following:

*SACHSISCHE ACCUMULATOR WERKE.

This is a quick formation process, in which highly diluted sulphuric acid is used, to which is added sulphuretted hydrogen (H_2S), the latter being the corrosive agent. This process yields excellent results, but it has the objectionable feature that the sulphuretted hydrogen which escapes is not only highly objectionable on account of its odor, but to a certain degree poisonous.

From the excellent results which plates so formed would seem to give, this would be a very satisfactory method, if the factory details for carrying on the formation in gas-tight rooms were properly worked out.

BECKMAN.

In this process, the plates are formed in an electrolyte consisting of a saturated solution of sulphurous acid in water. Sulphurous acid being a gas, the formation must take place under pressure, in order to prevent the gas from escaping from the electrolyte.

This is a quick formation process, and gives good results. There are no objectionable elements left which will attack the lead. The sulphurous acid, H_2SO_3, passes into sulphuric acid, H_2SO_4, under the electrolytic action. The sulphurous acid solution must be used immediately after its preparation, as it quickly oxidizes to H_2SO_4. In fact, both of these processes have the property of converting the lead attacking substance into H_2SO_4.

ELECTROLYTIC PROCESSES.

These processes are obsolete and it is questionable whether serviceable plates can be produced by them.

They are typified by the electrolytic deposition of sponge lead on a sheet or grid connected as a cathode and immersed in a solution of a soluble lead salt, a thin layer of PbO_2 forming at the same time on the anode. The tendency, however, is for the lead to go into solution from the anode, and layers of peroxide of practical thickness cannot be produced in this manner.

It may be stated here that after many experiments along the line of deposition of sponge-lead from litharge dissolved in alkaline

* German Pat., No. 127,275.

solutions, the author has become fully convinced that no successful battery plate can be so produced. Even compacting under the hydraulic press will not prevent rapid softening and disintegration after very few discharges.

AMALGAMATING PROCESSES.

There are many methods of amalgams in which lead is amalgamated with cadmium, potassium, or any metal which can afterwards be dissolved, and then extracted. When the amalgamating metal is thoroughly removed, in subsequent service the metallic lead is rapidly converted into PbO_2. These processes, however, have never proved satisfactory or practical, as traces of the alloying metal are, in every instance, left behind.

It is not to be supposed that this chapter covers every known method of Planté formation. It gives, however, most of the important and well-known processes, though, as previously stated, the proportions of chemicals used are in many cases probably incorrect.

It may be remarked that, after a system of formation has been perfected for a given type of plate, it does not always follow that this formation can be used satisfactorily on plates of other types, and it is sometimes difficult to transfer a formation process from one type of plate to another. The reason lies in the differences of exposed area, ability to hold the active material and amount of subdivision of the plates. Griscom * gave the results of some experiments which were made to determine the relative capacity of identical plates in the same cell. A cell having five positive and six negative plates was tested, in which the plates of like polarity were not joined directly together, but were connected, each set, to a common bus bar, with a resistance interposed between the plate and the bus bar. In this way, he was able to examine behavior of individual plates all joined in parallel and operated as a single cell. He discovered that in plates made of identically the same material, subjected to the same treatment and, so far as it is possible, made in every respect exactly alike, there was quite a difference of capacity. This difference ran as high as 30% on discharge down to 1.8 volts and when discharge is pushed below this point the difference became even higher. This differ-

* Transactions A. I. E. E., May, 1894.

ence in capacity resulted in a discharge of a positive of high capacity into those of low capacity. He explains the phenomenon by stating that the low capacity plate keeps on discharging, but at a lower rate than the higher capacity plate, and finally reaches a much lower electro-motive force. On opening the circuit the plate, which has not been discharged so far, rapidly recovers a higher voltage than its neighbor and therefore discharges into it. When plates are joined to a common bus-bar, they soon attain identical capacities in service.

CHAPTER XV.

PASTED ELECTRODES.

In 1880, Camille A. Faure, in France, and Charles H. Brush, in America, independently, and practically coincidently, produced the storage battery "pasted" plate, consisting of an antimonious lead grid, to which the active material was mechanically applied. The original Faure cell had both the positive and negative plate coated with minium or red lead, which is an oxide of lead, Pb_3O_4. A comparatively short time was required to change the Pb_3O_4 to Pb_3O_6 (or PbO_2) when connected as an anode, or to Pb when connected as a cathode, and the finished elements gave a high capacity per unit of weight.

In this latter respect the pasted plate battery is superior to the Planté. All batteries in which a minimum weight is required can best be produced by the Faure system. It has the disadvantage, however, that the active material on positive plates has a tendency to "shed" or drop away from the grid, and the life of a pasted electrode in continuous active service is short compared to that of a Planté plate.

This trouble has been partly overcome by the use of envelopes and shaping of grids to hold, more firmly, the applied material.

Numerous types of grids and varieties of active material have been devised and are used in the manufacture of pasted plates. So great is the number that only a few of the most important ones can be described here.

TYPES OF GRIDS.

(A) Grids for Pasting.

(1) *Framework of perforated sheets or latticework which is double, and in which the openings on the two sides of the plate do not come opposite one another.*

To this first type belong the Correns, Fig. 74; the grid used in the pasted plates of the National Battery Co., the Gould Co. and the Electric Storage Battery Co., Fig. 75; that of the Helios Co., Fig. 76.

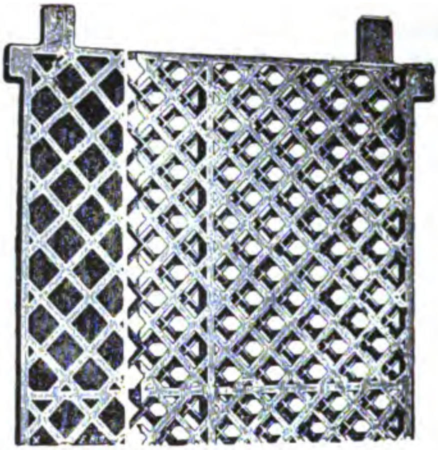


FIG. 74. Correns Grid.

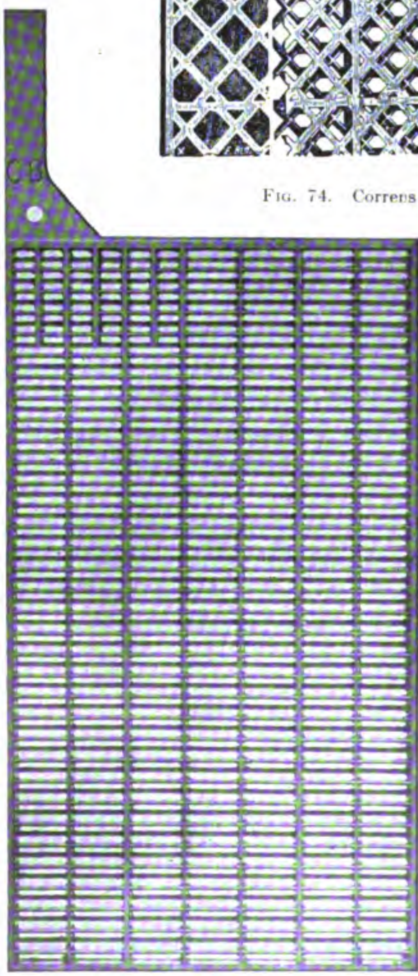


FIG. 75. National Grid—Positive.



FIG. 76. Helios Grid.

These grids clearly illustrate the type. The active material is put into the space between the two lattices which form the sides of the plate, being firmly compacted and pressed tightly against the ribs. When finished, the plate is smooth and solid, the active material being flush with the outer surfaces of the latticed sides.

(2) *Solid Perforated or Latticework Plates.*

To this class belong the Electric Power Storage Co.'s grid, which is shown in Fig. 77, and the Böse, Fig. 78. This last named

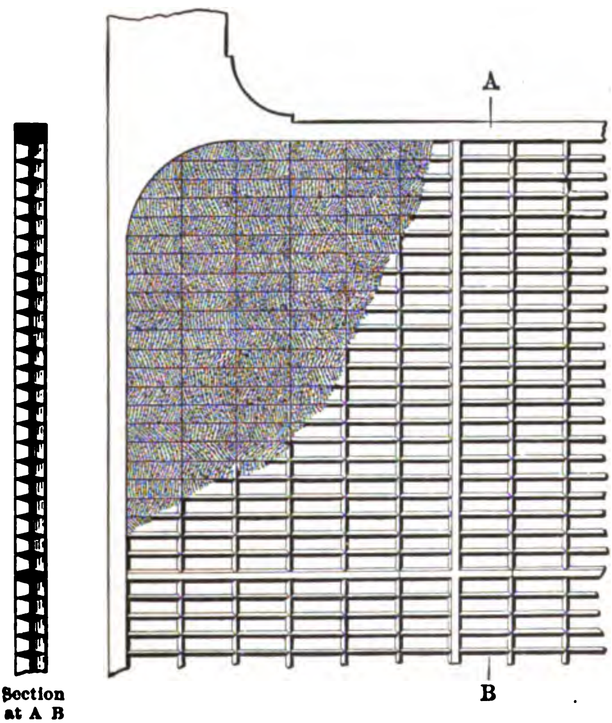


Fig. 77. Electric Power Storage Grid—Negative.

grid is provided with expansion slots, as may be seen. These slots are not filled with active material, but left open to give flexibility to the grid.

As may be seen, the sizes of the openings in the plates vary widely, and the designers' judgment seems to be the only determining factor as to the maximum area permissible between supporting ribs. As a matter of fact, the thickness of the plate, the character of the applied active material and the service battery is

to render all have an important bearing, though there is no definite law on this subject, and the question is one that can be settled only by experiment.

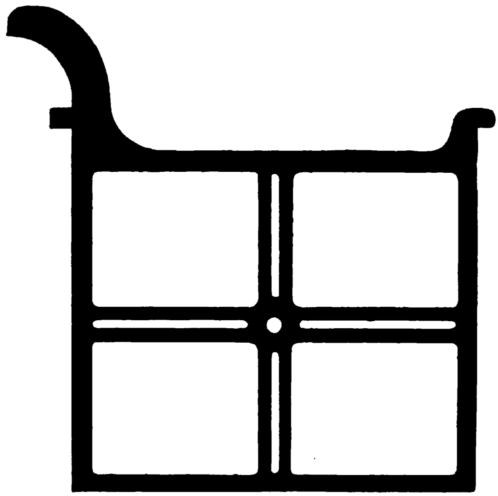


FIG. 78. Böse Grid.

(3) *Corrugated and Solid Recessed Plates Not Perforated.*

Under this heading come the Tudor, Fig. 80, and Khotinsky, Fig. 81.

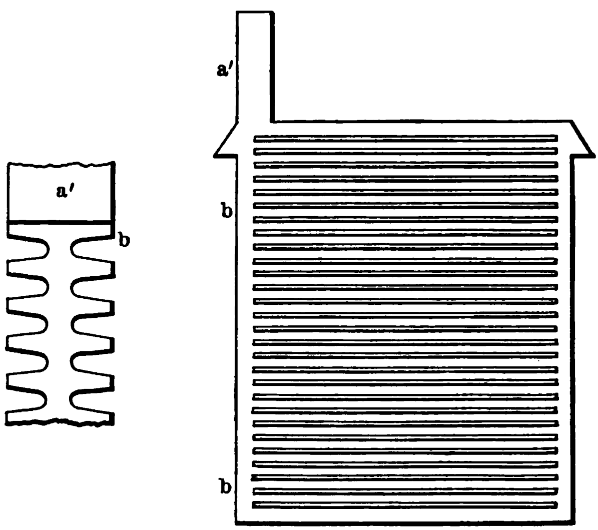


FIG. 80. Tudor Grid.

The active material is laid on both sides of the plate and pressed securely into the grooves or recesses. These grids are no longer manufactured.

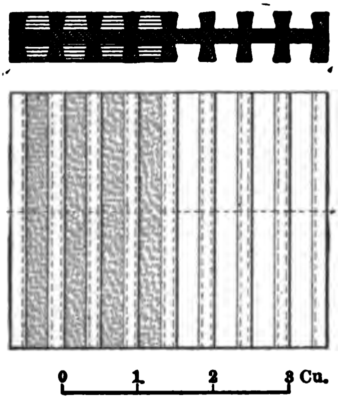


FIG. 81. Khotinsky Grid.

(4) *Combination of the Recessed and Perforated Groups.*

The Sperry grid, shown in Fig. 82, and the old type Exide negative, Fig. 83, are representative of this type.

The Sperry grid is made of a thin sheet of cast lead having strengthening ribs around the outer edges. Small triangular holes are punched through the sheet in such a manner that the punch cuts out only two sides of the triangle, and bends the cut portion out perpendicular to the plane of the plate. The resulting grid is perforated and has numerous projecting "fins" or teeth on each side, resembling a grater. The active material is applied under heavy pressure, which welds it together solidly into a cohesive mass, covering both sides of the plate and passing through the holes. Additional hold on the active material is furnished by the bending over of the fins, which clinch themselves over the outer surface.

The Exide negative plate was similarly constructed, except that the perforations are circular and the raised fins are cut radially and when pushed out stand around the periphery of the holes as shown.

(5) *Double Ribbed Plates.*

An example of this group is the Kölner Accumulatoren Werke, shown in Fig. 84.

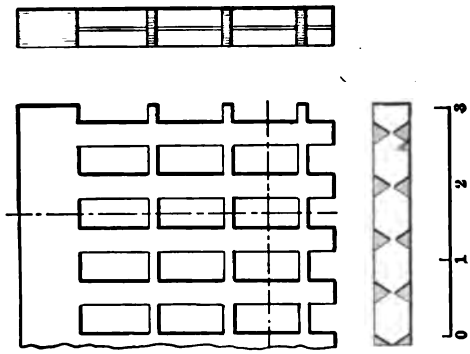


FIG. 84. Kölner Accumulator Werker Grid.

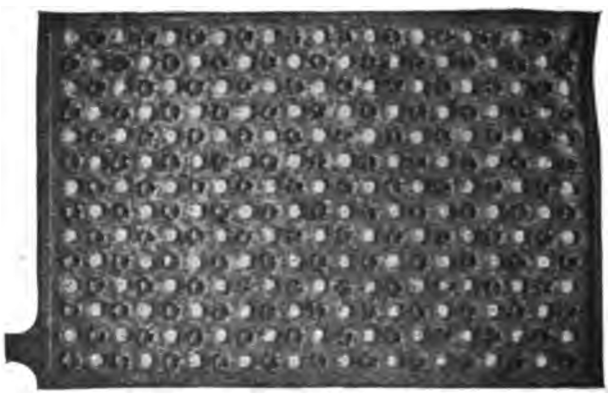


FIG. 83. Exide Grid — Negative.

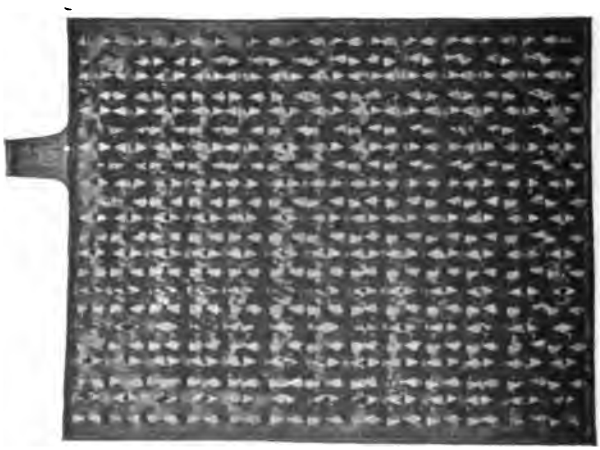


FIG. 82. "Sperry" Grid — Negative.

(6) *Plates Made of Ribs Having Enlarged or Projecting Portions.* Examples of these are: Hladik, Grünewalt & Co., Fig. 85, Accumulatoren Fabrik, Aktien Gesellschaft, Fig. 86.

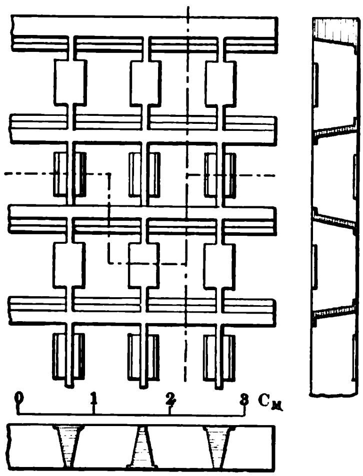


FIG. 85. Hladik, Grünewalt and Company's Grid.

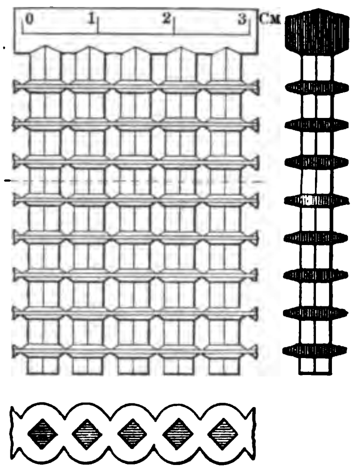


FIG. 86. Accumulatoren Fabrik A.G. Grid.

The projections serve the double purpose of retaining the active material and affording proper contact for conductivity.

All of these grids are filled up with sufficient active material to form a flat smooth plate.

(7) *Grids Having Horizontal Ribs Only.*

The Gelnhausen, Fig. 87, illustrates this style of grid. In this grid certain divisions at equal intervals, measured vertically, are left unfilled, to allow expansion and contraction and circulation of electrolyte.

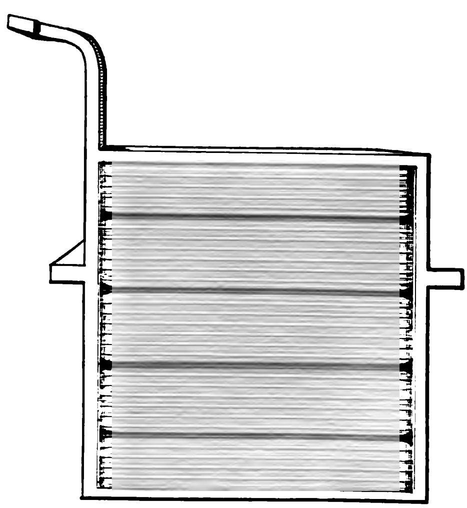


FIG. 87. Gelnhausen Plate.

(B) Grids Cast Around the Active Material.

In certain varieties of plates, the active material is formed into pellets, cylinders or other shapes which are laid in molds and the lead supporting grid cast around them. Usually the casting is done under pressure to insure good mechanical and electrical contact, freedom from blowholes, and elimination of impurities.

Under this group may be mentioned the Chloride, Fig. 88.

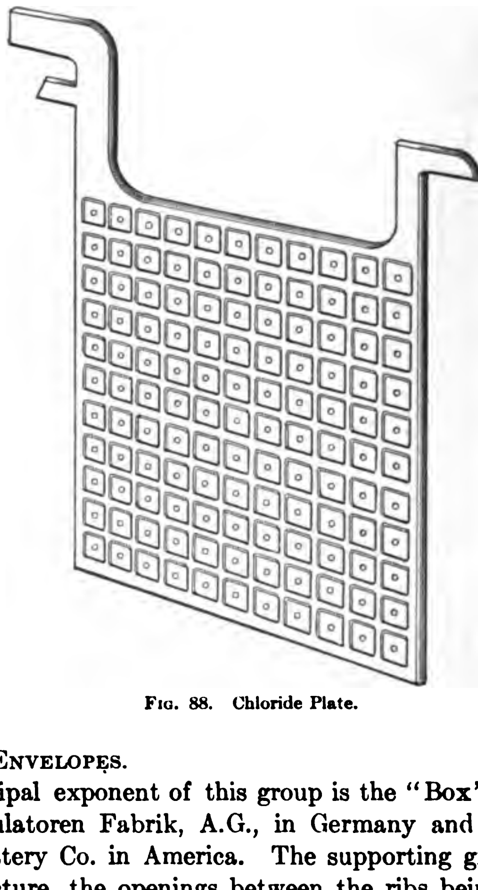


Fig. 88. Chloride Plate.

(C) Lead Envelopes.

The principal exponent of this group is the "Box" negative of the Accumulatoren Fabrik, A.G., in Germany and the Electric Storage Battery Co. in America. The supporting grid is a solid lattice structure, the openings between the ribs being square in form.

It is made up of two halves, each of which has one surface covered with a perforated lead sheet. The two halves are pasted full of active material and then riveted together. The plate,

therefore, has each face covered with a perforated lead envelope, as indicated in the picture, Fig. 89.



FIG. 89. "Box" Negative Plate.

(D) NON-METALLIC GRIDS.

Attempts have been made to produce pasted plates with the grids made of some substance other than lead.

The majority of the designers working on these lines were looking principally toward the production of a lighter battery than has been possible with lead grids, though a few were working with the object of confining the active material so that it could not drop away from its support.

The Standard Electric Accumulator Company's cell is an example of the second type, and is shown in Figs. 90, 91 and 92. Each electrode consists of two plates of unglazed, porous earthenware, having pockets formed on one face and channels on the opposite face. The pockets are filled with active material in sufficient quantity to project above the face of the plates.

Two plates of earthenware with a sheet of lead between them form an electrode. The active material being in contact with the

lead sheet, the latter is enabled to convey the current to or from the active portion. The reverse sides of the earthenware plates, in which the grooves are formed, are placed back to back, thus making vertical channels for the circulation of the electrolyte. The



Fig. 90.



Fig. 91.



Fig. 92.
American Electric Accumulator Company's Element.

elements are formed of consecutive electrodes, each alternate electrode being of the same, and adjacent electrodes being of opposite, polarity. The plates making up a complete cell are held firmly together by stout rubber bands to insure good contact

between the active material and the lead conducting plates and also to prevent the former from dropping out.

These various types of grids and special plates are shown to indicate the number of forms that the pasted battery has passed through. The list here is far from complete, as it is not intended to give a description of every grid that has been produced. To do so would require considerable space and could be of but little interest to the practising engineer.

Pure lead does not possess sufficient rigidity to make a suitable grid where the active material is mechanically applied. If the grid be slightly bent, the active material is likely to crack off. While this is also true of Planté plates, it is only so to a limited extent, as the active material is much thinner and usually formed on small surfaces independent of each other. It therefore becomes necessary to mix with the lead some metal or metals which will give this needed strength and resistance against distortion, but which, at the same time, will not materially change the voltaic characteristic of the grid.

The metal most commonly used is antimony, and the proportions of the alloy vary from 88% lead and 12% antimony to 98% lead and 2% antimony by weight. The most usual mixture is 96% lead and 4% antimony. Positive grids should have a lower percentage of antimony than negative grids.

Mercury and tin have also been used; for instance, the composition of the Worms grid is given as 96.5 lead, 2.2% antimony and 1.3% mercury. The Julien grid is composed of 92% lead, 3.5% antimony and 4.5% mercury; the Nevens grid is composed of 23% lead and 77% tin.

It seems to be generally supposed that these alloys are not attacked by the electro-chemical actions which take place, and therefore last indefinitely; this idea is, in a measure, fallacious.

It is true, however, that these alloys do not become oxidized as readily as pure lead, and the disintegrating action is therefore retarded.

Antimony and lead alloys are brittle and cannot be bent if the proportion of antimony exceeds 5 per cent. Under undue stresses they fracture with but little distortion.

CHAPTER XVI.

APPLIED ACTIVE MATERIAL MIXTURES.

ALL active materials consist primarily of pulverized lead or lead oxides (massicot, litharge, or red lead), to which is added a liquid to form a paste and in some cases other substances are incorporated.

The substances which are mixed with the lead or lead oxides may be divided into four classes:

(1) Substances which possess the property of causing the powdered material to harden or set (*e.g.*, dilute sulphuric acid).

(2) Substances which increase the conductivity of the resulting active material (*e.g.*, pulverized carbon).

(3) Substances which increase the porosity of the active material (*e.g.*, pulverized pumice stone).

(4) Materials which are themselves inactive but which bind together the active material and retard the disintegration thereof (*e.g.*, asbestos fiber).

Of these four substances the first must always be present, with or without any or all of the other three.

It is obvious that there exists an almost infinite number of combinations which practically attain the same objects. The following are some of the most important of the mixtures in actual practical use.

The oldest of the pasted active materials is litharge mixed with sulphuric acid.

The sulphuric acid used in the mixture is about 1.120 specific gravity, the proportion of liquid to litharge being 1 to 6. The mixing must be very thorough, and as little acid as possible used. The resultant mass appears as moistened, but not of such consistency that it can flow. After filling a grid, the plate is usually subjected to pressure and all the portions of the grid filled, the entire combination being tightly compacted. The plate is then dried in air. If the drying takes place at ordinary room temperature, from one to two weeks are required, according to the dryness of the air and thickness of the layer of active material. In some

cases, the drying is accelerated by placing the plates in ovens and maintaining therein a temperature of about 200° F. Usually the plates are again dipped in acid having a density of 1.100 and dried, to further harden.

After being fully dried, the plates are assembled and given a forming charge, after which they are dried and are ready for the market.

The active materials most commonly used are litharge (PbO) for pasting the negative, and minium or red lead (Pb_3O_4) for the positive. The negatives need only to be reduced to sponge-lead (Pb) by the action of evolved hydrogen in a dilute sulphuric bath. They are connected as cathodes with "dummy" plates of sheet lead as anodes, and current passed through the group.

The Pb_3O_4 on the positive plates is changed to PbO_2 by the addition of oxygen, which is supplied by connecting up against dummy plates, in a sulphuric acid bath, and passing current through the couple, the dummies being connected as cathodes, and the positive plates as anodes.

Böse makes a flat sheet of active material to fit into the grid shown in Fig. 78 by mixing the lead oxide and peroxide with alcohol, the latter having dissolved therein some distillate of coal tar. Anthracene is given as an example of the hydrocarbon which is mixed with the alcohol.

The resulting mixture is pressed into the grid, and dried in hot air ovens, after which the plates are hardened by immersing in dilute sulphuric acid. The final process is formation by charging and discharging.

Verdier uses a paste made of litharge mixed with glycerine and water.

After drying, the plates are treated in solution of sodium sulphate mixed with glycerine and water, and are finally formed.

Desruelles forms a paste from 60 parts red lead, 40 parts graphite, 25 parts pulverized porcelain and 10 parts white of egg. The graphite is intended to increase the conductivity and the pulverized porcelain is to give porosity. The albumen forms a good binding material.

Metzger makes a paste of lead oxide, dilute sulphuric acid and potassium silicate.

James uses the following compounds.

For the positive elements: Minium 85%, litharge 10%, carded asbestos 4%, and powdered carbon 1%.

For the negatives: Litharge 94%, carded asbestos 4%, sulphur 1%, and powdered carbon 1%.

Sperry makes a mixture as follows:

70 per cent of sponge-lead, 26% red lead, and 4% of ammonium sulphate. This is slightly moistened with dilute ammonia, but not sufficiently to more than make it into a dampish powder. The powder is put into a die, the grid on this, and another layer on top, and the whole compacted in a hydraulic press.

A variation of this mixture which has proven successful for both positive and negative plates is equal parts litharge and red lead with 6 to 10% of magnesuim sulphate. This mixture is also moistened with dilute ammonia water and compressed into the grid.

Litharge, Glycerine and Sulphuric Acid.

Litharge, when made into a paste with sulphuric acid and glycerine, forms an excellent active material, especially for the negative plate.

In mixing, the glycerine and concentrated acid are first mixed, using equal volumes of each. The resulting liquid becomes heated by reason of the chemical combination which takes place. After cooling, water is added in such quantity that it forms about 66% of the total volume of the liquid. The litharge is made into a stiff paste with this mixture, the proportion being about 870 cu. cms. of liquid to 4 kilos of litharge.

In applying this plate to the grid, it is usual to apply pressure by passing the pasted grid through rubber rolls which press out a portion of the moisture.

It has been stated that when formed into negative plates this material produces a tenacious, felt-like lead sponge superior to the brittle, granular lead sponge formed from the simple litharge and sulphuric acid paste.

Red Lead with Glycerine and Sulphuric Acid.

This mixture and method of application are the same as in the case just preceding, except that minium is substituted for litharge and less liquid is required to form a paste, the proportion being about 625 cu. cm. of liquid to 4 kilos of minium.

Pulverized Lead and Water.

A mixture of lead dust and water forms a good active material which sets like a cement and becomes hard and dense. The lead dust must be carefully handled and all air excluded from it.

The density of this mixture is rather too high to allow of porosity, and manufacturers who use this form of active material usually add crushed pumice stone, or some equivalent substance, to the mixture to correct this defect.

Litharge Mixed with Caustic Solutions.

If litharge be mixed with a saturated caustic solution such as potassium or sodium hydrate, the resulting paste will harden or set within a minute, at ordinary room temperatures, and so quickly does it harden that such a mixture cannot be worked.

If, however, the solution be diluted, the time required to harden increases proportionally to the degree of dilution and by reducing the strength of the solution the material can be handled and applied to the grid before it sets.

A proportion of one part of (fused) salt (sodium or potassium hydrate) to two or three of distilled water, by weight, is stated to be a satisfactory mixing solution.

Organic Compounds.

In addition to the use of glycerine, before referred to, such organic substances as lactic and butyric acids have been suggested as liquids with which to mix the lead oxides to form the active material paste. These mixtures are quick drying and therefore of value in manufacturing.

The paste can be compressed to a great density, thereby increasing its lasting qualities.

Heinemann patented* a mixture in which the oils of resinous trees, such as cypress and pine, are used as the liquid to make up the active paste. Oil of birch is also given as a desirable substance for this purpose.

Fitz-Gerald's "Lithanodes."

Fitz-Gerald has devised three mixtures which he terms "Lithanode" Nos 1, 2 and 3.

No. 1 consists of litharge mixed with solution of sulphate of

* Ger. Pat., 107,726, 1898.

ammonia to form a paste, or the two salts mixed together and afterwards made into a paste with water. The grids pasted with this mixture are "seasoned" — presumably exposed to the air— for some time, varying with the thickness of the active material. After the seasoning, the plates are painted with peroxide of lead in fine powder to render them conductive, and then connected as anodes to form positives, and as cathodes to form negatives, in a solution of sulphate of magnesia. The resulting plates are porous and have high conductivity.

Lithanode No. 2 consists of litharge mixed with sulphate of lead. This mixture hardens and sets firmly and is not affected by acid or water.

Lithanode No. 3 consists of litharge mixed with a solution of caustic potash.

Marchenay's Chloride.

The material invented by A. Marchenay, of Paris, and known as the *chloride* pellet or active material, belongs to the class in which the connection with the conducting support is obtained by casting the grid around pellets of the material which had been previously introduced into the molds. An electrode formed in this manner is shown in Fig. 88.

Lead chloride is made by dissolving finely divided metallic lead in dilute nitric acid, from which it is precipitated in the form of chloride of lead by adding hydrochloric acid. It may also be obtained by dissolving litharge in acetic acid and precipitating with hydrochloric acid.

The lead chloride is washed and then fused with zinc chloride and the resulting molten mixture is poured into molds in the form of square pellets, three-quarters inch on a side and five-sixteenths inch thick. These pellets are placed in position in the grid molds and the grid cast around them under pressure.

The plates are then assembled with zinc plates in a solution of zinc chloride and short-circuited. This causes the reduction of the lead chloride to spongy lead, with a peculiar fibrous texture, the fibers running perpendicular to the surface of the pellets.

The plates are washed in running water to free them from the last traces of chloride. The active pellets are left in a spongy condition and may be formed into positives or negatives as

desired, though in practice they are used exclusively as negatives.

It will be noted that in several instances above, the resultant sponge lead has a fibrous structure. Winship has shown that this condition always results when the lead salt and forming solution are such that the salt is slowly dissolved in the solution and the lead is deposited at approximately the same rate as new salt is dissolved.

It was long supposed that the fibrous texture of sponge lead formed from fused lead chloride was due to the crystallization on solidifying of the fused mass. The essential conditions for producing fibrous sponge lead are, however, as above stated.

In many instances, the formation of applied active materials requires as long a time to carry through as the improved Planté formations, as the red lead and litharge must be brought to the condition of PbO_2 and Pb respectively, by the liberation of oxygen and hydrogen.

Consider, for instance, a forming tank containing 20 negative plates each pasted with one-quarter of a kilogram of minium, making a total of 5 kilograms to be reduced from Pb_2O_3 to Pb.

To do this it is necessary to add 3 molecules of H_2 to each molecule of oxygen in the litharge to form H_2O, and leave only Pb behind.

Taking the atomic weights (gram equivalents) of the various compounds: 1 molecule litharge, Pb_2O_3, weighs $(206.5 \times 2) + (16 \times 3) = 461$ grams. 3 molecules of $H_2 = 3 \times 2 = 6$ grams. Since 6 grams of H will reduce 461 grams of Pb_2O_3, it will require 13 grams of H to reduce one kilogram of Pb_2O_3, and 5 kilograms require 65 grams of H.

One ampere hour releases 0.0374 grams of H; therefore to produce 65 grams of H takes $\frac{65}{0.0374} = 1{,}740$ ampere hours.

The composition of the litharge is taken as PbO, the degree of oxidation of commercial litharge and red lead not being very definite.

If the formula PbO represents the composition of the litharge, 240 ampere hours are required to reduce one kilogram to Pb, or 1,220 ampere hours to reduce 5 kilograms.

Since the rate of current flow through the plates must be limited to a certain density per square inch — varying with the type of plate, but usually about 6 amperes per square foot, both sides of

each plate being considered — these plates would be formed with about 15 amperes flowing, this being about the proper current for plates of such a size as to have pasted thereon 5 kilograms total of active material of usual thickness.

The length of time required, therefore, to form these plates will be $\frac{1740}{15} = 116$ hours, if the pasting material be Pb_2O_3. If the paste be made up of PbO, the time of formation will be $\frac{1220}{15} =$ 81.3 hours.

In practice, from 20 to 30% more electrical energy is required than the theoretical, owing to imperfect penetration and escape of gases which do not assist in the reduction of the oxide, but escape into the air.

Considering the positive plate, take as an example 20 plates, as before, in a forming tank, each being coated with one-quarter kilogram of red lead, giving a total of 5 kilograms on the 20 plates.

1 molecule of red lead (Pb_3O_4) = $(3 \times 206.5) + (4 \times 16) =$ 683.5 g.

Two molecules of oxygen must be added to produce PbO_2 (= Pb_3O_6) and the weight therefore = $683.5 + (2 \times 16) = 715.5$ g.

One gram of red lead requires $\frac{32}{683.5} = .04682$ g. of oxygen to change it to PbO_2, and 5 kilograms would therefore require 234.1 g. of oxygen. Since 0.298 g. of oxygen is released per ampere hour, the total ampere hours required to form these positive plates $= \frac{234.1}{0.298} = 787$ ampere hours.

Assuming, as before, a current flow of 15 amperes, the time theoretically required for formation would be:

$$\frac{787}{15} = 52\tfrac{1}{2} \text{ hours.}$$

At least 25% more energy, and therefore time, would be required in practice.

It is to be noted that all plates made by the Faure process must be "formed," just as is necessary in the production of Planté plates, and in many cases both the time of formation and the energy used are as great as necessary for the formation of the active material directly from the lead of the electrode.

It has been suggested and many attempts have been made to produce electrodes by forming quantities of active material in bulk, either by chemical or electro-chemical processes, and paste the formed active material on the grids.

This has, however, been found to be impossible, no matter how compacted the material may be or how intimately it be brought in contact with the grid. Under no conditions does it appear possible to avoid the formation of the individual plates.

CHAPTER XVII.

SEPARATORS AND ENVELOPES.

In order to space the plates apart and to prevent contact between adjacent plates and consequent short circuits, rod or diaphragm separators are used in all batteries except those in which the plates are covered with hard rubber or celluloid envelopes. In the latter case the non-conducting envelopes act as separators. Sheet separators should be as thin as is consistent with strength, and plentifully perforated, to allow thorough circulation of the acid when made of impervious material such as hard rubber.

Hard rubber, celluloid, wood and glass are the materials generally used.

Hard rubber is used on smaller sizes of cells, particularly those intended for traction work. They are generally made of a thin sheet, perforated and strengthened at intervals by ribs. The differences in the hard rubber separators manufactured by the various companies lie almost entirely in the disposition and form of these ribs. Fig. 93 shows the form of hard rubber separator generally used.

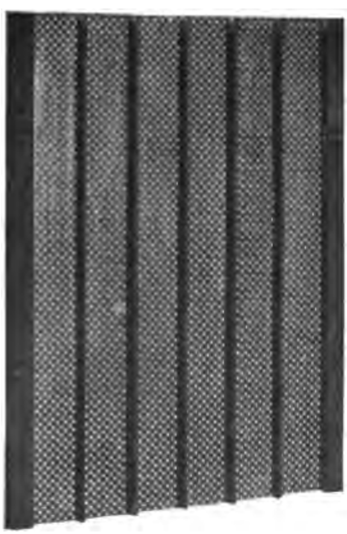


FIG. 93. Hard Rubber Separator.

A large number of small perforations is preferable to a smaller number of large perforations as, obviously, there is less possibility of particles of active material passing through the smaller holes.

Separators of this same general type, but made of celluloid, are used to some extent in Europe, but in America they are not

employed by any manufacturers of storage cells on account of their inflammability.

Glass separators are principally used in large cells and only in stationary batteries. These are simply a series of glass rods or tubes varying from $\frac{3}{16}$ to $\frac{3}{8}$ of an inch in diameter, depending on the distance of separation desired. In some instances a flange or ring is formed near one end of each rod. These rods are placed between the plates, extending vertically from above the top to below the bottom of the plates. The number of rods between each pair of plates is from 3 to 5, depending on the size of the plates. When provided with flanged upper ends they are held in position by strips of rubber through which the rods pass, there being a strip for each row of rods transverse to the cell. These rubber strips lie on the upper edges of the plates, while the rods are supported by the flanges on their upper ends, which rest against the upper surface of the rubber strips.

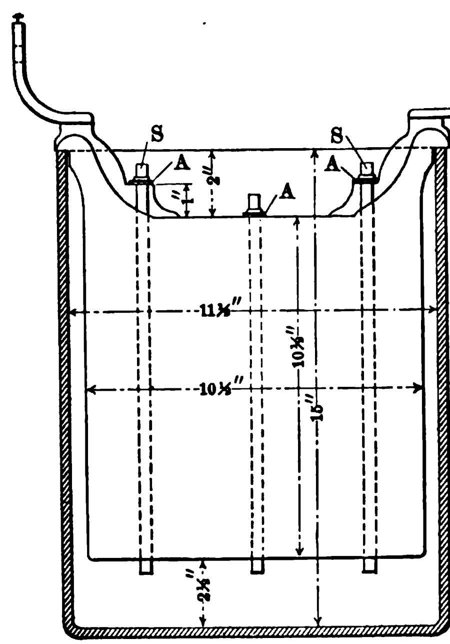


FIG. 94. Transverse Section of a Cell with Glass Separators.

Referring to Figs. 94, 95 and 96, S.S.S. are the glass rods, and A.A.A. the rubber strips which lie across the tops of the plates,

and through which the glass rods pass. The latter cannot drop through the holes in the rubber, as the flanges at the upper end serve as stops.

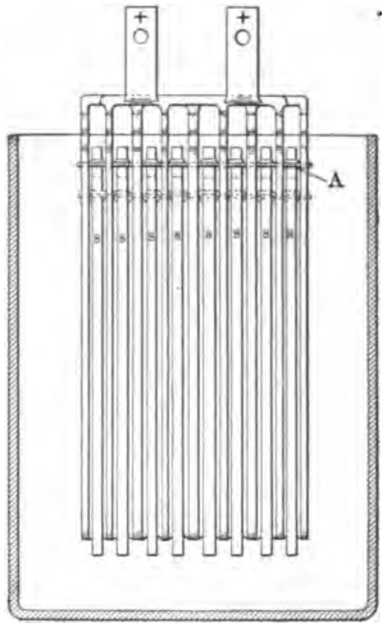


FIG. 95.

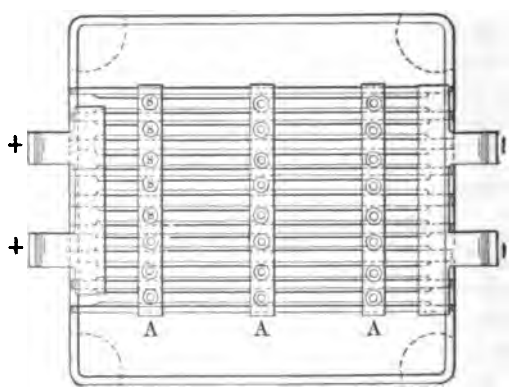


FIG. 96.
Plan and Longitudinal Section of a Cell with Glass Separators.

The rubber strips may be either hard or soft; both are used in practice.

Some manufacturers prefer to use rods without flanges, which are long enough to reach to the bottom of the cell and rest on it. Their upper ends are held in position by glass or porcelain retainers, which rest on small lugs cast on the upper edges of the positive plates.

With either glass rods or perforated sheets as separators, short circuits may form between the surfaces of adjacent plates. Tree-like growths or blisters sometimes form on the negative plates and may extend outward across the spaces between glass rods or through perforations until they make contact with the positive plate and thus short-circuit the cell.

Celluloid or rubber separators, which are used principally in portable cells, where the plates are very close together, may embed themselves into the soft sponge-lead of the negative plate and the active material press through the perforations sufficiently to make contact with the adjacent positive plate.

Wood separators are now commonly used in all types of cells, large and small, portable and stationary. They are generally satisfactory and efficient, but they must be carefully treated to remove impurities. There is some danger that acetic acid may be released from them at temperatures above 100 degrees F. and injure the plates. They are used extensively, however, and in spite of the possible injury mentioned, give excellent results.

These separators are simply thin wooden diaphragms and in vehicle cells are provided with light ribs which are intended to form vertical channels for the circulation of electrolyte. The thickness is usually from $\frac{3}{32}$ to $\frac{3}{16}$ inch. The height of the ribs, and therefore the depth of the channels between them, is about half the total thickness of the separator. Fig. 97 shows the vehicle type of wood separator. The ribs may be formed by grooving a solid sheet of wood, or they may be attached to a sheet of proper thickness by means of lead nails. In the latter case the grain of the ribs is transverse to the grain of the wooden sheet, and this form of separator is the stronger, but the more costly. Basswood is almost invariably used. Wood separators for stationary cells have no ribs; they are simply smooth sheets of basswood veneer.

They are supported by means of vertical wooden rods, which are slotted through from side to side so that the sheet can pass endwise through the slot. The rods are threaded on to the sheet,

and the number of rods on a separator, depending on its size. These rods serve both as supports and ribs or spacers, so that the sheets do not lie directly against the plate surfaces.

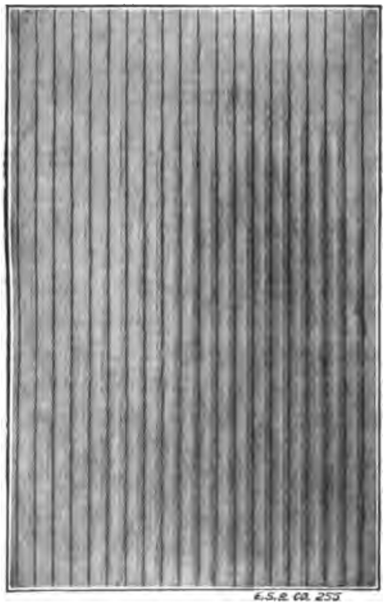


FIG. 97. Ribbed Wood Separator.

The separators are shorter than the depth of the cell, being only about $\frac{3}{4}$ inch longer than the plates, so that a support of some kind is necessary.

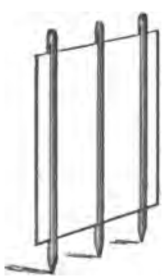


FIG. 97a. Wood Separator with Supporting Rods for Large Cells.

Fig. 97a shows a large size separator with three rods in place.

There are no perforations made in these separators, the electrolytic action taking place through the pores of the wood.

While the first cost of wood separators is very small, their life is short. Under the action of the acid the wood becomes friable and easily broken down into fine shreds. They will stay in place, however, and serve their purpose for several years if the plates are not disturbed, as the electrodes on either side form supports for the separators which retain their form. Replacements are necessary any time the plates are moved.

Wood separators, however, have the advantage of giving a positive separation between adjacent plates and effectually prevent contact between the opposite plate surfaces and short circuits from this cause.

The porous earthenware plates which form the supporting members for the active material in the electrodes of the type shown in Figs. 90, 91 and 92 obviously act also as separators, having the same characteristics as wood separators but, unlike the latter, being permanent.

In order to prevent the active material from shedding or loosening from the grid, envelopes are sometimes used on pasted plates. In case particles of active material loosen, they cannot leave contact nor fall to the bottom of the containing cell. Short circuits between adjacent plates by the accumulation of loosened active material in the bottom of the cell touching the lower edges of the plates is thus prevented.

In most instances envelopes are used only on the positives, though in some cases the negative plates are also covered.

Faure's original patent, dated January 11, 1881, mentions retaining coverings of "felt, asbestos, or other sufficiently porous material," for the purpose of holding the active material in contact with the grid. His early plates were covered with parchment paper and a second covering of stout felt. Neither one of these materials is now used, as the parchment paper lacks durability and the felt is expensive and neither is sufficiently porous.

Soft rubber, in perforated sheets, has been tried, but this is not suitable, owing to the fact that it rapidly disintegrates in the acid under the action of oxygen and hydrogen. In this connection, it may be here stated that soft, vulcanized rubber, in any form, soon becomes worthless if submerged in the electrolyte and should, under no circumstances, be used for permanent work.

The envelopes which are employed are made of lead, hard rubber, celluloid, asbestos cloth, glass wool and pyroxylin. Hard rubber, in thin perforated sheets, made in the form of a case into which the plate can be slipped, makes an efficient and durable covering. It is, however, expensive and is not much used.

Celluloid envelopes, made in the same way as the hard rubber ones, are also efficient, although this material decomposes somewhat under the action of the electrolyte and evolved gases.

Glass wool, which is glass in a finely divided fibrous state, has been used. It is packed into the spaces between the plates and serves its purpose fairly well. The mass is sufficiently porous to absorb enough electrolyte for the operation of traction batteries and also to allow of circulation. The method of separation is now obsolete.

Pyroxylin is made of open mesh cotton cloth, which is chemically treated with a mixture of nitric and sulphuric acids in equal parts diluted with 2 parts water. The compound formed is of the same general character as gun cotton, and burns so rapidly as to be practically explosive. A small quantity of nitro benzol is added to the bath in which the cloth is treated and the pyroxylin is thereby rendered inert. It is finally thoroughly washed and then wrapped around the positive plates. After undergoing the chemical treatment, it still retains its original appearance and texture. This material is not a successful covering, however, for the negative plate, as the action of the hydrogen soon disintegrates it.

The "box" negative plate, shown in Fig. 89, is surrounded by a perforated sheet lead covering which is an essential portion of this electrode.

CHAPTER XVIII.

CONTAINING CELLS.

CONTAINING cells of hard rubber, glass, celluloid and, in the case of the larger sizes of power station batteries, glazed earthenware or lead-lined wooden tanks are used.

The hard rubber jars are used almost exclusively for traction and portable cells. The thickness of the rubber varies from one-sixteenth to one-eighth of an inch. Hard rubber makes the best containing cell known for small sizes of elements, the only objection being its cost.

Celluloid makes an excellent containing cell, but owing to its inflammability, and consequent liability to take fire and burn with almost explosive rapidity, is used but little. A carelessly lighted match, or an electric spark — which latter is often made in changing connections at battery terminals — in proximity to a cell containing celluloid would constitute a source of danger.

Glass containing cells are suitable only for stationary batteries. For small cells, that is, not larger than $12 \times 12 \times 15$ inches, they are thoroughly satisfactory in every respect after once being installed, and are cheaper than any other kind.

Glass cells larger than the above size are made in ribbed glass and are much more expensive than the plain glass cells. Their cost and their tendency to crack under the temperature changes to which every cell is subject have caused engineers and manufacturers to avoid the use of glass cells in larger sizes, though some important installations have been made with these containers. Fig. 98 shows a large ribbed glass cell.

Recently, glazed earthenware cells have been successfully produced. They seem durable, rarely break, and appear to be superior to any other form of containing cell. Their high cost, however, has prevented them from being extensively employed. Also their durability has yet to be proven in long service.

For large size station batteries, heavy wooden tanks, lined with sheet lead, are almost universally used. The lining is generally of

from 3½ to 4½ pound lead, according to the size of the tank, that is, of such thickness that 1 square foot weighs from 3½ to 4½ pounds. The lead lining should be turned over the top edges of the tank and cover them.



Fig. 98. Ribbed Glass Cell.

The tanks themselves should be made of sound oak, pine, or teakwood throughly dried and boiled in paraffine or some equivalent compound, so that the pores are completely filled and there can be no absorption of spilled or leaking acid. Resinous wood, such as pine, has proven to be the most satisfactory and durable.

The parts of the tank should be dovetailed together, and the whole strongly assembled without the use of any metal fastenings. Fig. 99 shows a tank of this



Fig. 99. Lead-lined Wooden Cell.

description, with the elements in place. Too much care cannot be given to the protection of the wood. Each tank should receive two heavy coats of asphaltum paint, both inside and out, before the lead lining is put in. A final coat of the same paint is given after erection.

The joints must all be securely burned together by skilled workmen. A poorly constructed tank means continuous trouble and endless expense after being put into service.

When lead-lined tanks are used, the elements are always suspended by lugs, which usually are cast or burned onto the tops of the plates. These lugs rest upon glass sheets set vertically on either side of the tank, which rest on the bottom and project above the upper edges of the cell. These glass sheets are from $\frac{1}{8}$ to $\frac{5}{16}$ of an inch in thickness, depending on the size of the cell. Since the entire weight of the elements comes on these glass supports, a reinforcing strip of lead must be placed underneath them in the bottom of the tank, otherwise they would cut through the thin lead lining.

Rubber strips laid in the bottom of the cell are sometimes used for the glass supporting plates to rest on, instead of the lead strips. Either usage is good practice, though the lead reinforcement is more general.

Fig. 100 shows the dimensions of a lead-lined tank for elements $15\frac{1}{2} \times 15\frac{1}{2}$. The glass supports are seen on either side, and come within $\frac{7}{32}$ inch of the lead lining. The reinforcing strip of lead at the bottom of the glass sheets is 1 inch wide by $\frac{1}{4}$ inch thick. Wood separators are also shown. Note how the bottom, sides and the reinforcing sills underneath are dovetailed together.

It is customary to bore a hole through the wooden bottom of the tank so that any leak in the lead lining will manifest itself at once. The present tendency is to make the containing cells of such a depth that the lower ends of the plates are a considerable distance above the bottom of the tank, in some cases as much as 12 inches. This allows a large accumulation of sediment from the gradually disintegrating active materials, without the deposit piling high enough to make contact with the lower ends of the plates and thus short-circuit the cell. An approximate rule is that the distance from the lower ends of the plates to the bottom of the containing cell shall be equal to 40% of the length of the plates.

Where elements are contained in cells having this extra depth, it is necessary to clean out the cells only at widely separated intervals — usually at the expiration of the life of the positive plates when new positives are installed.

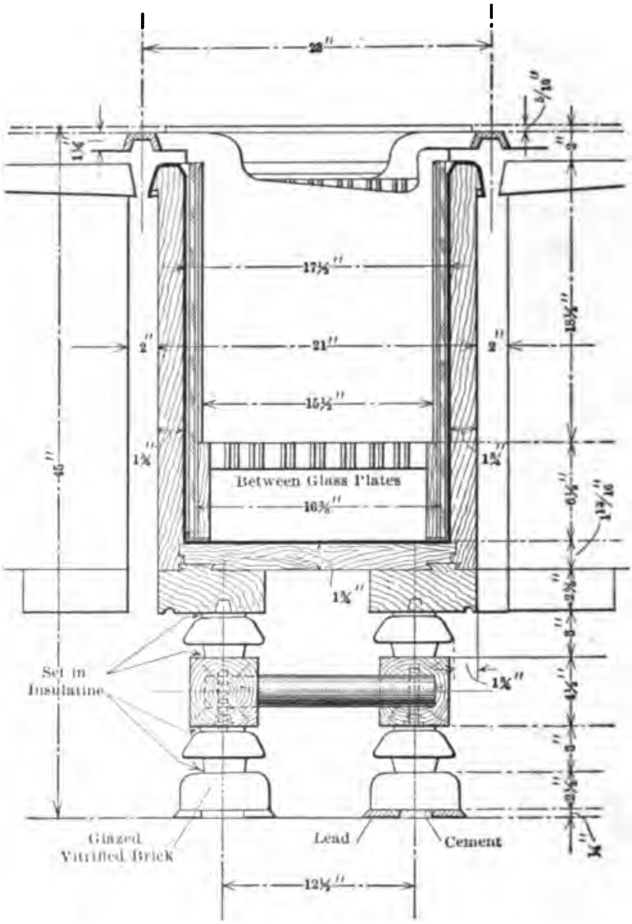


Fig. 100. Cell Construction with Wood Tanks.

Nearly all cells for stationary batteries have sufficient bottom clearance to admit an ample quantity of electrolyte. In the case of many portable batteries in rubber jars, the electrolyte space is so small that high density acid must be used, as set forth in Chapter VI.

CHAPTER XIX.

TESTING.

THE subjoined list gives the possible factors to be determined in storage battery tests. Some — such as internal ohmic resistance — are unimportant except from a theoretical standpoint. Most of those given are, however, important and should be determined.

(1) Weight of complete cell.
(2) Weight of elements.
(3) Weight of electrolyte.
(4) Dimensions of cell.
(5) Dimensions of elements.
(6) Normal and maximum charging rates.
(7) Normal and maximum discharging rates.
(8) Capacity at low, normal and rapid discharge rates.
(9) Variation of capacity with temperature.
(10) Variation of voltage with temperature.
(11) Internal ohmic resistance.
(12) Internal virtual resistance.
(13) Specific gravity variation of electrolyte.
(14) Loss of charge by leakage and local action.

These are all found by observation, and from them the following results are deduced:

(15) Charge and discharge rates per square foot of positive plate surface.
(16) Charge and discharge rates per pound of element.
(17) Charge and discharge rates per pound of complete cell.
(18) Capacity per pound of complete cell.
(19) Capacity per pound of element.
(20) Temperature coefficients of cell.
(21) Curves of charge and discharge.
(22) Efficiencies at various charge and discharge rates and temperatures.

(23) Relation of electrolyte density to ampere hours discharged.

(24) From all of foregoing deduce the commercial value of the cell under test, and determine whether or not its characteristics are suitable for the service that it is intended to perform.

(25) Durability. This is made last because of the long time required, and should not be undertaken until all the other points are settled.

These various tests will now be considered in detail:

(1) *Weight of cell* is found by weighing the complete cell, inclusive of connectors.

(2) *Weight of elements* is found by partly discharging say one-fifth capacity, after giving a full charge to reduce all sulphate, removing from electrolyte and then drying with blotting paper, after which they are weighed. Do not keep the negative plates out of the liquid any longer than necessary.

(3) *Weight of electrolyte* is = (1) − (2) − (weight of jar).

Dimensions of cell (4) *and elements* (5) are determined by ordinary measurement, the elements being measured when taken out of the cell to be weighed. (4) should include all dimensions of separators, height of lower edge of plates above bottom of jar, clearance between plates and sides and ends of jar, height of edge of jar above tops of plates; (5) should include area of plate surfaces, areas of conducting portions of the grid, area of lugs — these two last to determine if the current densities are within the limits of good practice — 150 to 200 amperes per square inch.

After determining (1) to (5) inclusive, connect up the battery for making the other tests. The usual way of connecting is shown in Fig. 101.

G is a source of charging current.

R_1 a variable resistance in series therewith.

B, the test cell; A, a two-way reading ampere meter; V, a low reading voltmeter; S, a double pole, double throw switch, and R_2 a variable resistance connecting the two lower terminals of the switch together.

By means of R_1 the charging current, which flows into the battery when S is in its upper position, can be regulated. On discharge, the switch is thrown to its lower position, and by means of R_2 the current outflow may be given any value desired.

The voltmeter V should be permanently connected across the battery terminals, and cadmium readings made with a separate instrument. If only one voltmeter is to be had, however, readings may be taken at intervals by placing the contacts against the

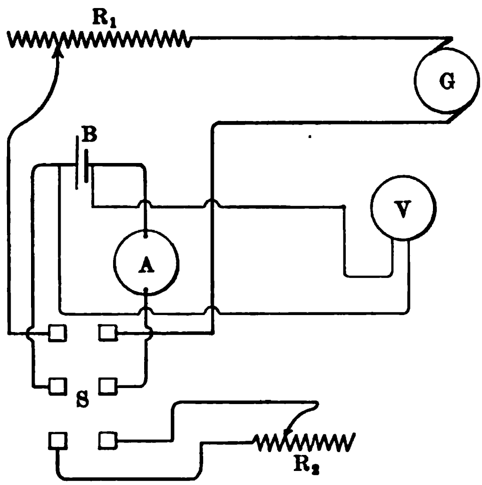


FIG. 101. Connections for General Test.

lead lugs of the battery plates. The contacts should be bright and sharp, and pushed strongly against the lead lugs so that good contact is made.

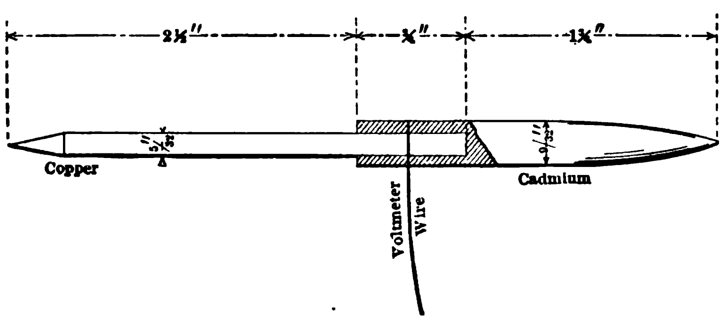


FIG. 102. Cadmium Contact Piece.

A good arrangement for taking cadmium readings is to make two voltmeter contact pieces, as shown in Fig. 102. A short piece of hard copper wire about five thirty-seconds of an inch in diameter is screwed or pushed into a piece of cadmium about nine thirty-seconds of an inch in diameter. The lead to the voltmeter

is fastened about the middle point. The device is improved if it be taped about two inches along its length on either side of the point where the voltmeter lead is joined on, and it is also well to cover the cadmium completely with a rubber tube perforated with small holes. If two pieces of cadmium cannot be obtained, one piece will serve, but in this case the voltmeter connections will have to be reversed to take the negative plate readings when the battery is charging. With the two, composite, contact pieces, the voltage across the cell is read by pressing the two copper ends against the positive and negative lugs. The cadmium reading to positive is then made by taking away the contact at the negative plate and immersing the cadmium portion in the electrolyte, care being taken that it does not touch any plates or connections. If the cell be *discharging* the negative reading to the cadmium can be made by keeping the cadmium piece in the electrolyte and moving the contact from the positive plate over to the negative. At the end of charge, the cadmium in the liquid must be removed, and the copper end of the contact piece pressed against the negative lug, while the contact which was on the positive lug is taken away, and its cadmium end placed in the electrolyte.

(6) *The charging rates* are usually given by the makers, but in absence of any instructions, they may be determined approximately by calculation, taking .040 amperes per square inch of positive plate surface as normal. This can be checked after a few trials by the length of time elapsing from beginning to the end charge, as evidenced by the voltage rising to 2.5 and vigorous evolution of gases, called "boiling." The eight-hour rate is usually taken as the normal in power station cells, and the five-hour rate in motor car batteries.

The maximum charging rate is that at which the cell will absorb energy without heating more than 25 degrees F. above surrounding atmosphere, or excessive gassing. Usually this will be found to be not greater than the two-hour rate.

(7) *The normal discharge rate* may be taken as equal to the normal charge rate — usually taken as the eight-hour rate. The maximum discharge rate should usually be not greater than the one-hour rate except on short discharges followed immediately by charge, as on regulation work, in which case the cell may be worked as high as the 20-minute rate.

After determining (1) to (7) inclusive, the battery should be given several cycles of charge and discharge at the 8-hour rate, to bring it up to good working condition, before going on with the tests following.

(8) *The capacity at normal discharge rate* should first be determined. Charge at normal rate until the cell reaches its final voltage, which will be in the neighborhood of 2.5 volts, and gases vigorously. The final voltage is reached when prolonging the charge does not cause any increase in voltage nor acid density. Note acid density and temperature during charge, at intervals of about twenty to thirty minutes. The voltage observations should be at intervals of about three minutes for the first quarter of an hour, then of six minutes, until the voltage becomes steady, after which twenty or thirty minute intervals will be often enough until the point is reached where the voltage begins to rise rapidly, when the readings should be about six minutes apart. The plotting of curves from readings is greatly facilitated if the observation intervals are 3, 6, 12, 15 or 30 minutes, as these are decimal fractions of an hour.

When the cell is fully charged, then discharge, keeping the current constant throughout the time of discharge. Note acid density, temperature and voltage as before, the voltage readings being taken at short intervals at the beginning and towards the end of discharge, and at longer intervals where the fall is slow and steady. The constant current of discharge multiplied by number of hours duration up to the point where the voltage drops to 1.8 gives the ampere hours capacity. This result, multiplied by the *average* voltage during discharge, gives the watt hours capacity.

The temperature must be kept as nearly constant at 70 degrees F. as possible.

Cadmium readings should be taken at the beginning and end of charge (the latter before current is cut off); just after beginning discharge; at the end of discharge, before the current flow is stopped; and occasional readings should be taken during charge and discharge. Should the voltage on charge be 2.5 and the voltage between the negative plate and cadmium zero, or the reading be positive to the cadmium, the cell cannot be considered as fully charged, and the charge should be prolonged until the negative is brought up to its proper value. In cells where the positive electrodes have supporting grids of antimony-lead alloy,

the difference of potential between the cadmium and the negative should be about 0.05 volt, at the end of charge, while with elements made up of pure lead, the voltage should reach 0.12 or 0.15, the cadmium being positive to the sponge lead.

If on discharge the voltage between the negative and the cadmium reaches .25 measured oppositely to the reading on charge, before the cell voltage drops to 1.8 the discharge should be considered as ended. Should this occur on more than one discharge, either abnormal local action or deficient capacity in the negative plate is indicated.

After finding the capacity at the normal rate, discharges should be made at the 1, 3, and 5 hour rates, and the capacity at these rates determined. Observations, of course, must be taken at more frequent intervals when discharging at high rates.

(9) *Variation of capacity with temperature.* The best way to make this test is to bring the temperature of the room to the desired point, and allow the battery to stand until it attains the room temperature. On charging, it will tend to heat, but by considerably reducing the charging rate towards the end of charge, the cell will cool down to practically the initial value if the sulphate be completely reduced.

The cell should be shielded from drafts by screens or a box, so that the temperature will be maintained constant within reasonable limits.

If a more accurate test is desired, the cell should be set inside a box or tank filled with water. Inside the box, and below the surface of the water, is placed a steam pipe, by means of which the water can be brought to any temperature higher than that of the room, and, in turn, raise the temperature of the battery.

With care, the temperature can be maintained constant throughout charge and discharge, by controlling the admission of steam to the heating pipe.

(10) *Variation in voltage with temperature* would be observed at the same time as variation in capacity, and under the same conditions.

(11) *The internal ohmic resistance* is very difficult to determine accurately, because it is so small compared with that of any commercial measuring instrument, and also because it is itself a variable. Many methods have been devised for measuring it, three of which are herewith given. They all, however, require

careful and painstaking work to produce accurate results. The observations should be repeated many times and under various conditions.

Sheldon's Method, devised by Dr. Samuel Sheldon, is one of the simplest, the only apparatus required being a telephone receiver, a slide wire bridge, and an auxiliary, non-inductive resistance, of known value.

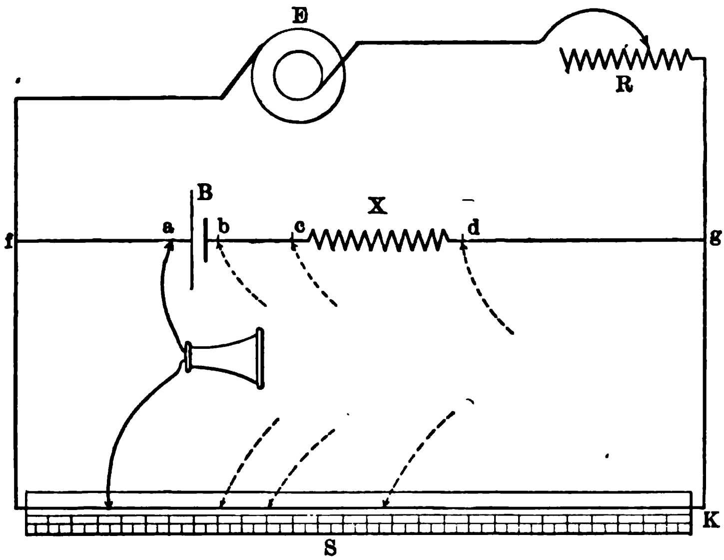


FIG. 103. Connections for Sheldon's Test.

The test cell is connected up as shown in Fig. 103. E is a source of alternating current, B the battery under test, X the known resistance, and S the slide wire bridge. R is a resistance to adjust the strength of the current. An alternating current of constant value — about twice the normal charging current — is sent through the battery and resistance X. The voltage between the extreme ends of the slide bridge is equal to the drop from f to g.

The first reading is made with the terminal, t, of the telephone receiver at a (that is, at the point where the connection is made between the conductors and the battery lug), the other terminal p being moved along the bridge until a point is found at which the receiver gives the least sound. This point on the bridge is then at the same potential as point a. Similarly, readings on the bridge are found for points b, c and d.

The drop from a to b is that due to the ohmic resistance of the cell, and is proportional to the reading on the bridge at b, minus reading at a. Likewise the drop through X is proportional to the reading at d minus reading at c. From this it is evident that

$$x : r :: (d - c) : (b - a), \tag{53}$$

whence

$$r = \frac{X (b - a)}{d - c} \tag{54}$$

r being the internal resistance of the cell.

It is neither necessary to measure the current passing, nor to know the absolute values of a, b, c and d in volts. If these readings be simply *lengths* intercepted between the pointer p and the end h, the ratio still holds.

If the lengths are measured from the end K, then the formula becomes

$$r = \frac{X (a - b)}{c - d}. \tag{55}$$

It is desirable that X should be small, in order that the drop across the bridge be also small, and consequently the drop across a, b will show an appreciable length on the bridge. It is also essential that the bridge wire be homogeneous, and of equal resistance per unit of length over its entire length. Owing to the errors introduced by the effects of capacity, this method is only approximate.

Condenser Method.

The connections and apparatus for testing by this method are as shown in Fig. 104.

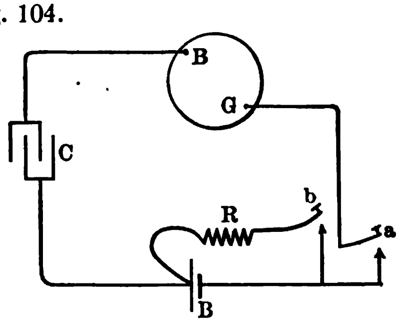


FIG. 104. Connections for Condenser Test.

C is a condenser, BG a ballistic galvanometer, a and b keys, B the test cell, and R a known resistance which should be low

enough to permit full normal current to flow when connected across the battery. On depressing key a, the condenser receives a charge proportional to the cell electro-motive force and a corresponding throw of the galvanometer needle is produced. Still holding a down, depress b and the potential at the battery terminals is decreased because of the drop, due to the current flowing through it and R. A partial discharge of the condenser will take place, causing a reverse throw of the galvanometer needle.

Calling the throw first obtained T, and the second t, $T - t = t_1$ is the throw which would have occurred if b were first depressed, and then a, the condenser being without charge. After securing the first two readings, discharge the condenser by short-circuiting its terminals, re-connect it as before, depress b and then a, and compare the direct reading obtained with the computed value of $T - t$. If they do not check, the observations should all be repeated until they are sensibly equal.

The resistance of the battery $= r = \dfrac{R(T - t_1)}{t_1}$ deduced as follows:

T is proportional to the electro-motive force = E of the cell.

t_1 is proportional to $E - Ir$, where I is the current flowing when b is depressed.

Then $T : t_1 : : E : (E - Ir)$. (56)

$$I = \frac{E}{R + r} \text{ whence } E - Ir = E \frac{Er}{R + r};$$

$$T\left(E - \frac{Er}{R + r}\right) = t_1 E;$$

$$t_1 = T - \frac{Tr}{R + r};$$

$$Rt_1 + rt_1 = RT + rT - rT;$$

$$rt_1 = R(T - t_1);$$

$$r = \frac{R(T - t_1)}{t_1}. \tag{57}$$

Rimington's Method.

The connections for testing by this method are as shown in Fig. 105.

R_1, R_2 and R_3 are resistances and B the test cell in the four arms of a Wheatstone bridge. In the same arm with R_1 an auxiliary

cell is inserted, giving an electro-motive force to oppose that of cell B. G is a galvanometer — which is preferably a sensitive d'Arsonval instrument — S is a switch or key. R_1 should be of about 10 ohms resistance and R_3 about 0.1 ohm.

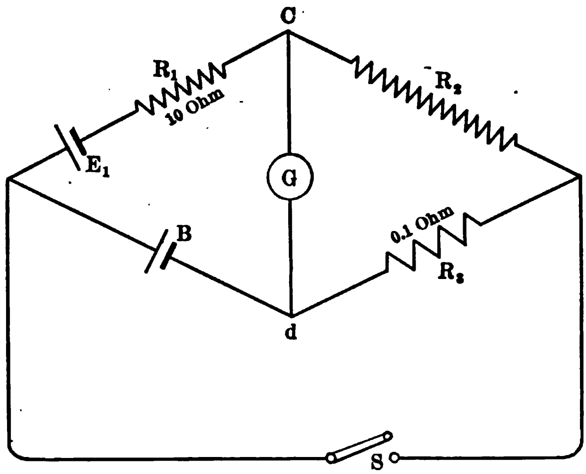


FIG. 105. Connections for Rimington's Test.

On making the connections, a small deflection will be observed, due to a slight difference in the electro-motive force of the two opposing cells. On closing S a different deflection is observed. R_2 must be adjusted until the deflection is the same whether S be open or closed. Then the internal resistance of

$$B = r = \frac{R_1 R_3}{R_2}, \tag{58}$$

neglecting the internal resistance of E, which is inappreciable as compared with R.

The effects of polarization cause certain changes in the deflection, which require some rather nice manipulating to eliminate.

If polarization sets up in the test cell when switch S is closed, a current will pass from c to d because of the decrease in the electro-motive force of the cell, and the galvanometer will be correspondingly deflected. A decrease of R_2 tends to cause current to flow from d to c, and produce a deflection in a corresponding direction. Therefore R_2 must be gradually diminished until an impulse is observed in the latter direction. This impulse will be

immediately followed by a movement in the opposite direction, caused by polarization of the test cell. R_2 should be gradually increased until a point is reached at which this impulse disappears, and this value is the correct one for R_2.

(12) *The internal virtual resistance* is found by connecting the cell as shown in Fig. 101.

Note voltage on open circuit; call this V_1. Then throw switch to upper position, allowing a definite current to flow into the cell, and note increase in voltage, calling this V_2.

Then open the switch and observe again the open circuit voltage. The voltmeter pointer will not drop back immediately to its final value, but will come down slowly. Wait until the needle movement ceases before taking the reading. This sometimes is as long as 75 seconds. The last reading should be the same as V_1. Again close switch, sending same current through as before, and note voltage; call this V_3. Then by means of the adjustable resistance, R, send an increased current through the cell, and again observe the voltage; call this V_4.

From the first measurement:

$$R = \frac{V_2 - V_1}{I_1}, \tag{59}$$

I_1 being the current flow in amperes.

From the second observation:

$$R = \frac{V_4 - V_3}{I_2 - I_1}$$

in which I_2 is the increased value of the current.

Also test by taking the voltage on open circuit and throwing the switch to the lower position, so that the cell discharges. The virtual resistance in this case will be

$$R = \frac{V_1 - V_5}{I_3}, \tag{60}$$

in which V_1 = Voltage on open circuit; V_5 = Voltage when discharging, and I_3 the current flowing.

On repeating the experiment by increasing the current outflow in a manner similar to the test with inflowing current, the resistance becomes

$$R = \frac{V_5 - V_6}{I_4 - I_3}, \tag{61}$$

in which V_5 is the voltage before increase of current flow; V_6 that after increase; I_3 the current flowing before increase, and I_4 that after increase.

Further test consists in adjusting resistances R and R_1 so that the current flow will be the same on charge as discharge; call this current I_0. Throw the switch to its upper position, and as the charging current passes in, note the voltage. Call this V_0. Then quickly throw the switch to its lower position so that the current flows out from the cells, and take the voltage reading; call this V.

Then $$R = \frac{V_0 - V}{2 I_0}. \qquad (62)$$

This last test should be tried for various values of current and at various points of battery charge. The final determination of R is an average of the various values determined by the different tests mentioned. These values should not be greatly different for the same point of battery charge, but will vary somewhat for different points.

(13) *Specific gravity variation of electrolyte* is observed preferably by the insertion of a flat hydrometer in the liquid in the cell. If, however, a flat instrument is not obtainable, a small quantity of electrolyte may be drawn from the jar by means of a rubber bulb or syringe, and put into a large test tube, into which the hydrometer may be placed.

The electrolyte withdrawn is then poured back into the cell. Always stir the liquid before putting in the hydrometer or removing from the cell, in order that the specific gravity observed will be that of the entire mass of liquid.

(14) *The loss of charge* on standing idle is found by charging the cell up to 2.5 volts, and then discharging down to 1.8, noting capacity, temperature, voltage and acid density. Then charge again to 2.5, and set aside for 48 hours. Bring to same temperature as that of the previous test, and discharge down to 1.8. Repeat this test, setting aside for 60 hours and again for 120 hours. The loss is, of course, equal to the capacity immediately after charge, minus that of the discharges taken after the periods of rest.

The cell should be carefully insulated so that the loss of charge may be an indication of the amount of local action. Cadmium

readings on discharge will show which of the plates has suffered the greatest loss, and consequently the most local action.

In working up the data obtained, the quantities (15) to (19) are easily deduced.

In making comparative tests of capacity per pound weight of several batteries, there should be the same number of plates in each cell. If one cell should contain more plates than the others, it would have a marked advantage in such a test, for the reason that the end negative plates weigh nearly, if not quite, as much as the other negatives, although they give only about half the capacity of the other negatives, and they therefore tend to increase the weight of the cell, without a corresponding capacity increase. The fewer the number of plates the greater will be the proportionate increase of weight, from this cause. Therefore, no comparative test is fair to all batteries, unless each contains the same number of plates.

No capacity test is of value unless the temperature at which discharge takes place is specified, and in comparative tests all discharges should be made at the same temperature.

(20) *The capacity temperature coefficient* is a factor which, if the capacity at one temperature be multiplied by it, the product resulting will be equal to the *increase* in capacity for each degree increase in temperature, or, expressed algebraically,

$$Ct_2 = Ct_1 + jCt_1, \qquad (63)$$

where Ct_1 = capacity at any given temperature, j, the temperature coefficient, and Ct_2, the capacity at a temperature one degree greater.

If the capacity at several temperatures be found, then the temperature coefficient = j can be computed as follows:

By definition,

$$Ct_2 = Ct_1 + Ct_1\,(t_2 - t_1) \times j, \qquad (64)$$

in which Ct_1 = capacity at given temperature, t_1; Ct_2 = unknown capacity at some higher temperature, t_2; and j the temperature coefficient.

Solving:

$$j = \frac{Ct_2 - Ct_1}{Ct_1 \times (t_2 - t_1)}. \qquad (65)$$

It will be found that j will vary somewhat for different stages of temperature increase; and it will be greater from a low tem-

perature to one only moderately higher, than from a high temperature to one still higher. In other words, the increase of capacity per degree increase in temperature is not a linear function, but varies, decreasing as the temperature rises. Between 50 degrees and 80 degrees F., however, the limiting temperatures usually found in practice, j is practically constant.

There will also be a different coefficient for each *rate* of discharge, the greater values being for high rates.

(21) *Curves of charge and discharge* are plotted in the usual manner, from the voltage observations made during the various tests. From these, the general performance of the battery may be seen, together with the various changes which take place during the periods of charge and discharge.

(22) *Efficiencies* at normal rates are determined from observations on charge and discharge, and the ratio of the amount of energy supplied to that delivered. Efficiencies at rapid discharge rates, however, must be the subject of special tests, consisting of several cycles of charge and rapid discharge.

Start with the cell fully charged, and end with it in the same condition, the number of charges and discharges being equal. The efficiency will be equal to the sum of the amounts of energy delivered by the several discharges, divided by the sum of the amounts of energy put in on the several charges. Owing to the fact that the energy required for charging is somewhat indeterminate, because some energy is lost by the release of gases from the electrodes, an accurate determination of efficiency requires several tests — not less than four — all taken at the same temperature. The mean of the results of these tests is the cell efficiency.

(23) *The relation of electrolyte density to the ampere hours discharged* is easily computed from the discharge data and corresponding hydrometer readings. Usually the curve of variation in acid density is plotted on the same sheet with the voltage curves, and if these latter be for a constant current of charge or discharge, the density for any ampere hour output can be read off directly. Fig. 106 is an example of a specific gravity curve combined with the voltage curves. The discharge rate is 16 amperes. At the beginning of discharge the density is 1.280; at the end of the first hour, or 16 ampere hours, the density is 1.253; at the end of the second hour, or 32 ampere hours, 1.226, and so on, the final value at the end of discharge being 1.148.

Except at very low rates of discharge, the readings of the hydrometer will not show the true specific gravity of the electrolyte because of the slowness of diffusion, as has been previously discussed. The hydrometer readings are, however, useful to show the rate of diffusion, which is indicated by comparing the curve of hydrometer readings with the line drawn from the point of maximum density at the time of full charge, to the point of minimum density, which latter is found by discharging the cell at the 8-hour rate and allowing it to stand four hours. Obviously, the nearer the curve of hydrometer readings approaches the line of actual change in density, the better is the diffusion.

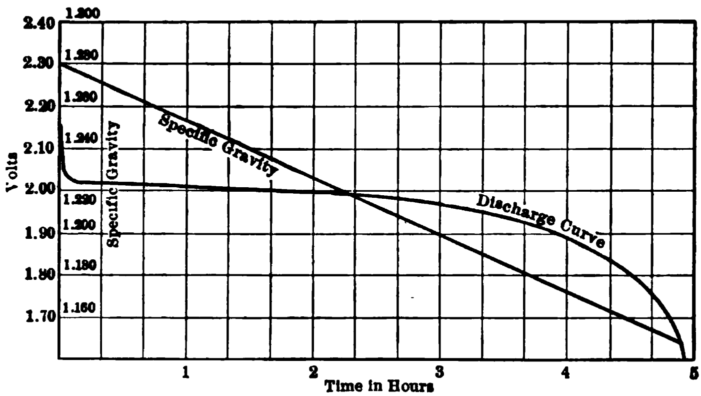


FIG. 106. Variation of Specific Gravity of Electrolyte with Discharge.

In practice, a knowledge of this variation in density is useful, as giving an indication of the state of charge left in the cells when they have been partly discharged, provided the cells are in good condition. If the density is found to be appreciably less than it should be, as shown by tests when in good condition, the cell is undergoing discharge, either from leakage or internal discharge, and the resulting formation of sulphate decreases the density. Therefore, if the density range and variation be known, it becomes a useful check on the condition of the cell. Increased density merely shows evaporation.

(24) With a previous knowledge of the requirements necessary in a battery for it to successfully meet given conditions, and all the foregoing data in hand, a careful consideration of all the questions involved will show whether or not the battery is adapted for the service it is intended to give.

(25) *Durability.* No test other than that of continual use, extending over a long period — possibly years — can definitely determine the durability of a battery. It is, however, possible to form a reasonably correct idea by subjecting pasted electrodes to 150 cycles of charge and discharge, of 6 hours each, the half cycles (charge or discharge) being at the 3-hour rate. This requires 900 hours, or about 38 days of continuous operation, and a change of connections from charge to discharge, or vice versa, every 3 hours. To perform this work by hand and continuous personal observation would require two or three shifts of men, and be both tedious and costly. A simple automatic apparatus, however, does the work, and a daily inspection of only a few minutes is required when this device is used.

This apparatus consists of an electrically operated time switch, double pole and double throw, and is made of a clock, two electro-magnets and an oscillating shaft carrying contacts which dip into mercury. Figure 107 shows the general arrangement

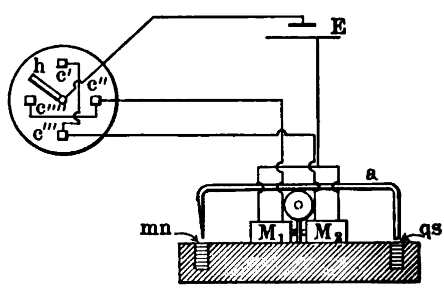


FIG. 107. Time Switch — Elevation.

and connections of the automatic time switch. The face and hands of the clock are removed, and a sheet of fibre is substituted for the face. Screwed thereto are four contacts, c, c, c, c, insulated from all other parts, and equally spaced 90 degrees apart around the circle. They are slotted where the holding screws pass through to allow accurate adjustment. In place of the hour hand is substituted a light, strong copper arm having a contact piece at its end, which can make light yet firm and definite contact with c, c, c, c. A brush of fine wires will not do, as it lacks definiteness of point of contact.

M_1 and M_2 are small electro-magnets, of about 2 ohms resistance, operated by a cell E. mn and qs are mercury cups forming the

terminals of a double pole, double throw switch, a plan view being shown in Fig. 108. Figure 109 shows the method of connecting up the test cell. G is a source of current; R_1 and R_2 adjustable resistances; B the battery to be tested, and S the two-way switch.

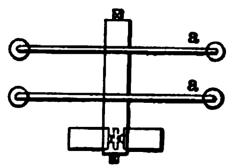


FIG. 108. Plan of Time Switch.

A good way to make the mercury switch cups is to bore holes about 1 inch deep into a piece of 1½ inch board, as indicated in Fig. 107.

The oscillating switch is made of two pieces of heavy wire, a, a, fastened at their middle points to the small short shaft d, as shown, and insulated therefrom. This shaft is supported on

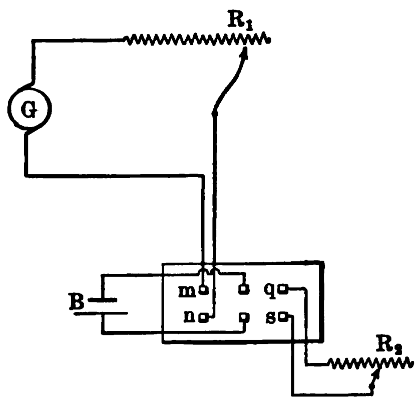


FIG. 109. Connections for Time Switch.

proper bearings, and on its lower side has fastened an iron armature oscillating between the two magnets, M_1 and M_2. It is obvious that if M_1 be excited, the armature will be attracted towards the left, the shaft will rotate slightly, and contact will be made at q and s, while it is opened at m and n. If M_2 be excited, the reverse operation will take place.

The operating cell E, which is used to excite the magnets M_1 and M_2, and may be any type of battery, primary or secondary, is so connected through the clock contacts and hand that when the hand touches c and c′, M_1 is energized, and when it touches c′ and c‴, M_2 is energized.

Adjust the contacts by timing with a watch, so that the interval from the making of one contact to the making of the next is exactly three hours. Then connect up as shown.

Adjust R_1 and R_2 so that the current flow through them on closing the charge or discharge circuit is the 3-hour rate, and the test is ready to begin.

As a precaution, a revolution counter may be connected to the oscillating shaft d, to show the number of cycles through which the cell has been operated.

If pasted plates at the end of 150 discharges are still in fair condition, they may be considered as durable. The appearance of the plates will indicate whether or not they bear promise of much subsequent work. Planté plates, however, should have a total life of 1500 to 2500 discharges at the 8-hour rate or 2500 to 3500 at the 3-hour rate. Therefore any durability test should cover at least 800 to 1000 discharges, which would take over four months.

CHAPTER XX.

ASSEMBLING AND INSTALLING.

In assembling plates together, joining the edges of the lead linings in tanks, or making any lead joint or connection, the two pieces to be joined should always be flowed or "burned" together. This operation consists in subjecting the edges to be united to a high temperature, such that the lead is melted and flows together, forming in effect a lead weld, without flux or alloy.

This is accomplished in practice by means of the oxy-hydrogen blowpipe, which is merely a small copper or brass tube of about $\frac{3}{16}$ of an inch outside diameter and $\frac{1}{8}$ of an inch bore. One end is capped with a small nozzle of from $\frac{1}{64}$ to $\frac{1}{32}$ of an inch opening, the other end being covered with wire gauze. The tube is usually bent near the nozzle end to about a 30 degree angle, to facilitate the application of the flame on different forms of work. The end which is covered with wire gauze is inserted into a rubber tube, which leads the mixture of air and hydrogen gas to the blowpipe.

The gauze is to prevent the flame at the nozzle from running back to the gas reservoirs. A stopcock in the line of the rubber tube or on the blowpipe permits the adjustment of the strength of the flame.

The rubber tube goes from the nozzle to a branch at which two rubber tubes are connected, one connecting with the hydrogen, the other with the air reservoir. Stopcocks are also inserted in each of the branch tubes, so that the mixture can be varied. The rubber tubes are about one-quarter of an inch inside diameter.

Hydrogen is generated by the action of sulphuric acid on zinc or iron, the former being generally used.

Arsenic in zinc produces a particularly poisonous gas and should be avoided.

The apparatus for producing hydrogen is shown in Fig. 110.

A and B are tanks, the latter being air tight. The bottom of A is about 4 feet above the bottom of B. A lead pipe, C, runs from the bottom of A into B, extending downwards nearly to the bottom of B; d is a perforated partition or false bottom in B,

raised a few inches above the tank bottom, on which scraps and small pieces of zinc are placed, entrance to the tank being effected through the tight-closing opening f. Sulphuric acid is poured into A and flows through tube C into B. When its level has risen in B up to the zinc, its chemical action on this metal is to form zinc sulphate, releasing free hydrogen gas. This generates a pressure in B, which, on reaching a certain value, forces the acid out through C, up to tank A, leaving the zinc uncovered, and the generation of gas ceases. If any gas be withdrawn through h, the pressure in B will fall, some acid will flow down from A and cover the zinc, resulting in the liberation of more gas. Thus the

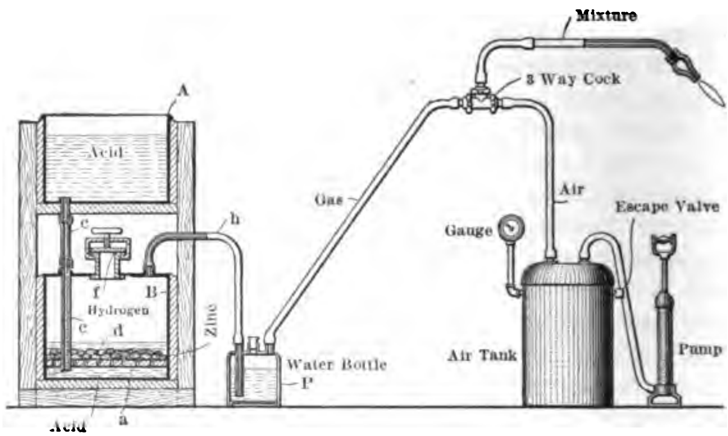


FIG. 110. Oxy-Hydrogen Burning Apparatus.

generator is entirely automatic, and the pressure is always constant, being that due to a column of acid having a height equal to the difference between the levels of the liquid in the two tanks. The usual pressure is about three pounds per square inch.

From the generator the gas passes through h to P, which is a vessel filled with water, through which the gas must all pass before going through K to the blowpipe. P serves both to purify the gas and also to prevent the flame from getting back from the blowpipe to the generator. The oxygen is supplied by pumping air into a reservoir or tank, a small, automatically controlled power pump or a hand pump being used.

Electrolytic hydrogen generators are also employed, though they are found more frequently in Europe than in America. It is

claimed that hydrogen can be produced more economically in them than in the ordinary chemical producer just described.

An important advantage that the electrolytic producer possesses is that both oxygen and hydrogen are obtained and the blowpipe flame is much hotter when pure oxygen is used than when it is diluted with nitrogen, which is inert and which forms 78% of air. With the hotter flame and pure gases, the work of lead burning is expedited and the labor cost reduced.

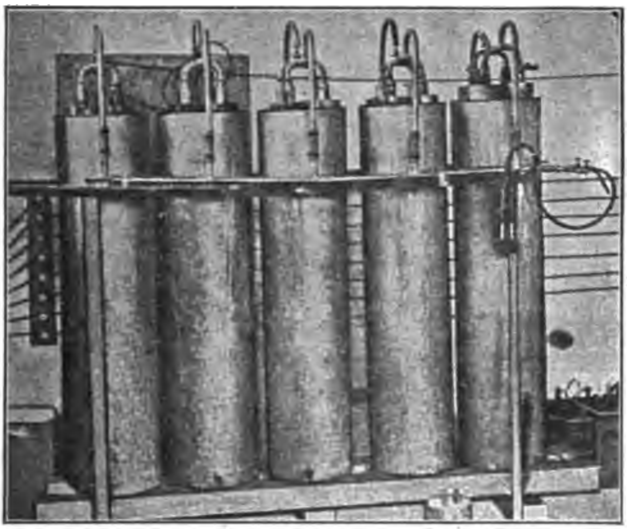


FIG. 111. Electrolytic Hydrogen Generator.

Figure 111 is a picture of an electrolytic gas generator designed by M. U. Schoop of Germany. Figure 112 is a diagrammatic scheme of the electrical and gas connections. AAA are containing cells of lead, glass or any acid resisting material. Immersed in each cell are four lead tubes, GGGG, which are perforated near their lower ends. These tubes have their surfaces greatly augmented by ribs or other means, such as are employed in making Planté electrodes, so that a large surface is exposed to the electrolyte.

Each lead tube is placed in a larger containing cylinder of glass, the upper end of which is hermetically sealed. The length of the enclosing glass cylinders is slightly less than that of the lead tubes, so that at the lower ends of these electrodes the lead tubes project

down below the ends of the glass cylinders. Connected to the top of each glass cylinder is a glass tube which connects with one of the pipes for conveying the released gases to the gas holders. Four of these electrodes are placed in each containing cell and are arranged in pairs as indicated in Fig. 112. The electrolyte is made up of water and sulphuric acid, the density being about 1.240.

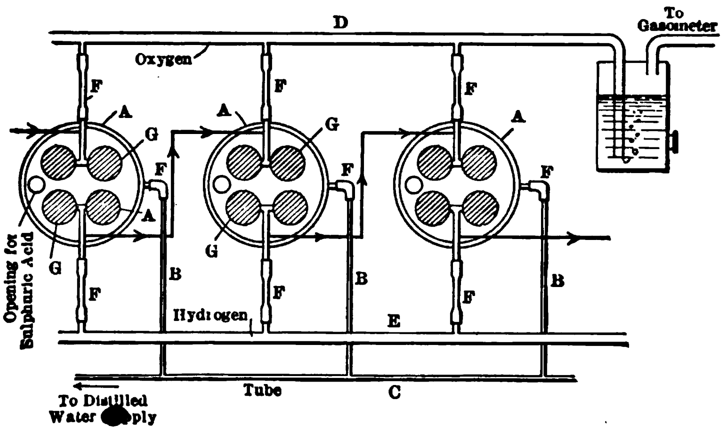


FIG. 112. Diagram of Connections of Electrolytic Hydrogen Generator.

Usually 5 cells are connected in series, the electric current entering the first cell by one pair of electrodes and passing through the electrolyte to other pair, thence to a pair of electrodes to the next cell and so on through the series. Oxygen and hydrogen gases are evolved at the positive and negative poles respectively, and are caught in the surrounding glass cylinders, from which they are conveyed by the connecting tubes to gas holders, there being one holder for each of the two gases.

Interposed in each main gas tube is a cleaning device which is simply an air-tight vessel filled with limewater, and having two pipe connections at the top. The one through which the incoming gas enters the cleaner, extends downwards to a point near the bottom of the vessel, while the other begins at the top of the vessel and is well above the level of the liquid in it. The gas passing through the cleaner, bubbles up through the water and passes out of the outgoing tube, thus being thoroughly washed. The limewater also neutralizes any particles of sulphuric acid which may be carried off with the gas.

Distilled water is added as required to take the place of that decomposed into gas. A small glass tube communicating with each of the cells and with a reservoir which can be filled when required, supplies the water as needed. This tube also serves to maintain the level of the electrolyte at the same height in every cell. Its small size makes the resistance through it from cell to cell so high that there is no appreciable current flow through it.

The potential per cell is from 2.5 to 3.5 volts. Actual tests show that the energy required to produce 1 cubic meter of hydrogen and one-half cubic meter of oxygen under a pressure equal to a water column one meter high, is 11 horse-power hours.

This system cannot be used without gas holders, owing to the fluctuations of pressure which would result from taking the gas directly from the cells.

Where lead burning is to be done at points of installation, compressed hydrogen and oxygen are shipped in steel bottles. The pressures are about 1700 lbs. per square inch, and consequently a considerable quantity of gas can be transported in a comparatively small vessel.

The electric arc has been suggested for lead burning, and at one time the author made some investigations in this direction, but found that the work, though satisfactory, was not so good as could be done with the oxy-hydrogen flame, as the heat was too much localized. The chief difficulty with the arc, however, and one that makes it wholly impracticable, is the effect on the eyes of the workman. Smoked glasses and shields of all kinds were tried, but after a few operations the operator had to stop and for several minutes was practically blind from the dazzling light, though the effect soon passed off. The use of the arc was therefore abandoned.

In cases where the amount of work done is small, the lead joints can be made by using a special alcohol blow torch or a hot soldering iron, with tallow or rosin for a flux. The tin solders and zinc chloride fluxes must be avoided. In large installations, however, the construction is carried on with the assistance of a portable oxy-hydrogen apparatus or compressed gases in steel bottles.

When battery parts are received at the point of erection from the factory, they should be very carefully unpacked. Rough handling may bend plates, or break separators and containing cells.

After unpacking, clean the plates, jars, separators and other parts thoroughly. A hand bellows should be used to blow all

dirt or loose excelsior from the electrodes. The separators should be rubbed clean with a cloth and the containing cells washed clean. Wood separators are shipped wet, in oil-cloth packages. They must not be allowed to dry out, and therefore must be unpacked only when the plates are in position and ready for the insertion of the separators. The tanks should be filled with electrolyte as soon as possible after putting the separators in place.

If any plates are bent, straighten them by compressing between two wooden boards which must be large enough to fully cover the plates. Apply pressure gradually with a screw press or some equivalent device. Never under any circumstances attempt to straighten plates by a blow from a hammer or mallet, as the active material will be loosened and fall off.

The individual battery plates are assembled together to form a complete cell, by "burning" to a common lead bar or strip, all the plates of like polarity; there being, of course, two bars for each cell, one being joined to the postive, and the other to the negative plates.

The usual practice in the small and moderate sizes of cells is to make the plate connectors in the form shown in Fig. 113.

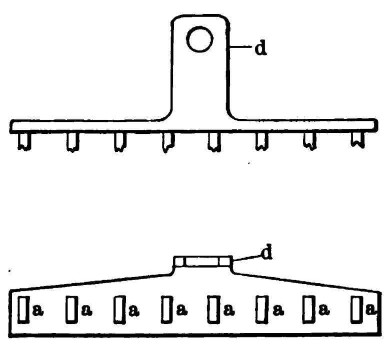


Fig. 113. Strap Connector.

A is a plan of the connector which is cut out of sheet lead or cast in the form shown. The rectangular holes, a, a, a, a, are the size of the lugs on the battery plates, and are spaced the distance apart that the plates of one polarity are to be.

The projecting end, d, is turned up at right angles to the plane of the connecting strip as indicated. The upper ends of the plate lugs are inserted into the holes and the lugs and strip are burned

solidly together, thus making a complete element. A positive and negative element are put into a cell, the plates being properly spaced by the connecting strips and adjacent plates prevented from touching by some form of separator. The cells are joined together by burning the ends d, d, or by bolts.

If the cells be moderately large — say of 350 ampere hours capacity and above — two joining straps may be required in order to give sufficient current-carrying capacity.



FIG. 114. Element in Glass Jar.

When bolt connectors are used to join the terminal straps together, the nuts are made of hard brass or iron, and covered with lead. The studs are of iron or brass, but not lead covered, being protected by the nuts on either end and the straps through which they pass.

Figure 114 shows a small element in a glass jar with the terminal straps arranged for bolt connection, and Fig. 115 an installation of cells so joined together, the latter figure showing cells with double connecting straps.

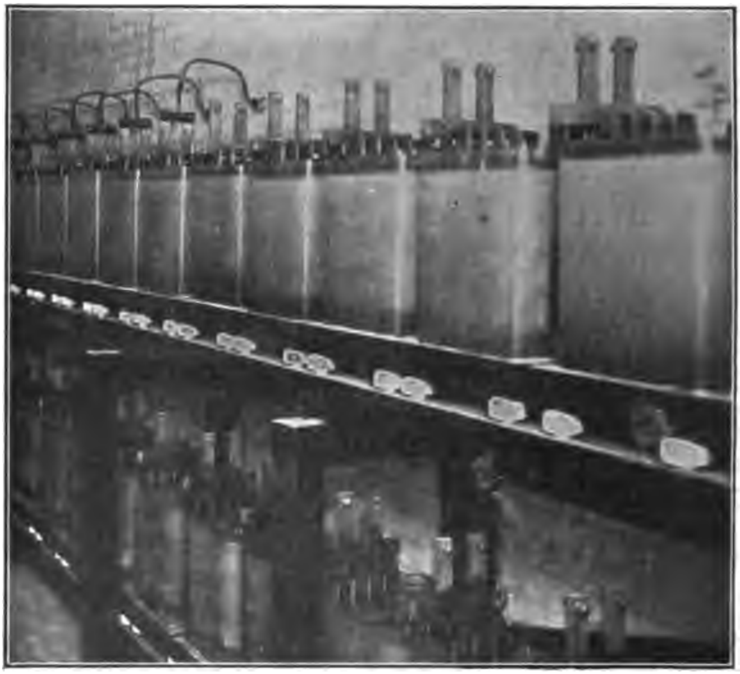


FIG. 115. Installation of Cells with Bolted Connectors.

When connections are made with bolts, they should be inspected every month for the first two or three months, as the soft lead of the straps and nuts tends to " flow " under pressure, and joints that have been made tight occasionally flatten out and loosen after a time.

When bolted joints are to be made and the nuts are lead covered, never attempt to force a nut on a stud when it does not screw on easily. If the nut is hard to get on, run a tap into it or a die over the stud, so that the nut will turn easily. Either paint all bolt connections with asphaltum or smear with a good layer of vaseline, so that the copper studs will be protected against the action of the acid spray if loose joints tend to expose them.

Scrape all parts that are to make contact so that they are bright, smooth and clean. Use a regular plumber's scraper, which will remove the lead uniformly. A knife or a light sharp-bladed tool should not be employed, as it will chatter over the surface of the lead and merely roughen the parts.

When working around a cell, cover it in some manner. A heavy canvas cloth is useful for this purpose. Particles of metal or other substances may fall into the cell, also nuts or studs may be dropped into it, and these are difficult to remove, as they fall between the plates and may roll under them. Also an accidental blow with a wrench may break a containing cell. These possible accidents will be obviated by covering a cell when doing any work near it.

It may here be noted that all metal work near batteries must be lead covered. Any metal in a battery room subjected to acid fumes should be painted with acid-proof paint. No ironwork should be used in a battery room except where unavoidable. If iron parts are necessary they should be well painted. The best paint to use is some bituminous compound, such as asphalt. Lead coverings are of but little value unless thickly applied, as thin coatings of lead are liable to be abraded in working and erecting the parts and these abrasions form pockets for the accumulation of acid vapors which will corrode the underlying metal.

In larger size cells, strap connectors and assembled elements are too heavy to be handled, and the assembling is done at the point of installation. The tanks are first put in place, then the plates put in and spaced by the glass separators, after which connecting, or so-called, bus bars are put into position, and the plate lugs burned solidly to the bars. Each bus bar has welded to it one set of positive plates which are in one tank, and one set of negative plates which are in the immediately adjacent tank. The cells are thus joined in series, and the path traveled by the current from one cell to the next is very short. This method of assembling the elements is made clear from Figs. 98, 99, 116 and 117.

Figures 98 and 99 show single tanks with their two sets of elements joined to their respective bus bars, while Fig. 116 shows a plan of a single cell with a portion of the adjacent cells on either side. In this cut p, p, p, p are the positive plates and n, n, n, n the negatives. B, B are the lead bus bars having a cross section such as shown in Fig. 117. The negative plates in the tank (Fig. 116)

are all welded to the left-hand bus bar, while the positive plates in the left-hand adjacent tank are welded to the same bus bar.

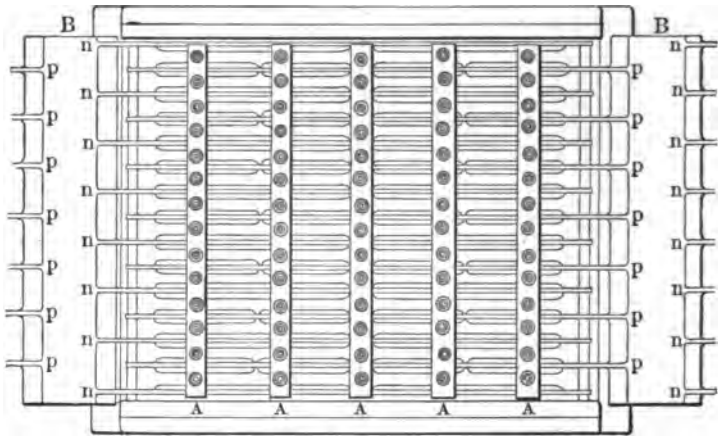


FIG. 116. Plan of Cell with Welded Connections.

The right-hand bus bar has, connected to it, the positive plates in the tank and the negative plates of the cell on the right hand. Thus the elements are connected in series.

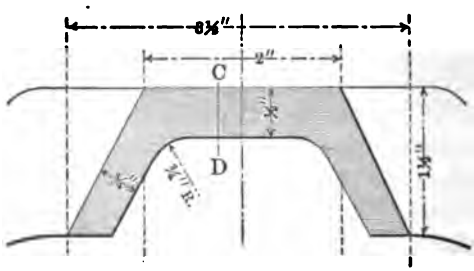


FIG. 117. Cross-section of Bus bar.

The manner of doing this lead burning is depicted in Figs. 118 and 119. Figure 118 shows what is termed a "burning set-up."

A and C are the adjacent sides of two lead-lined tanks, P is the left edge of a positive plate in tank A, resting on the glass supporting sheet S. Its terminal lug, which is beveled, projects towards the bus bar B, located midway between the two tanks.

N is a negative plate in tank C, also supported on glass sheets and having its terminal lug projecting towards the bus bar B.

Underneath the bus bar B and each set of plate lugs is placed a flat iron bar E called "burning irons." These rest on wooden wedges W, which in turn are supported on a heavy timber H, and this rests on the upper edges of the tanks. By means of the

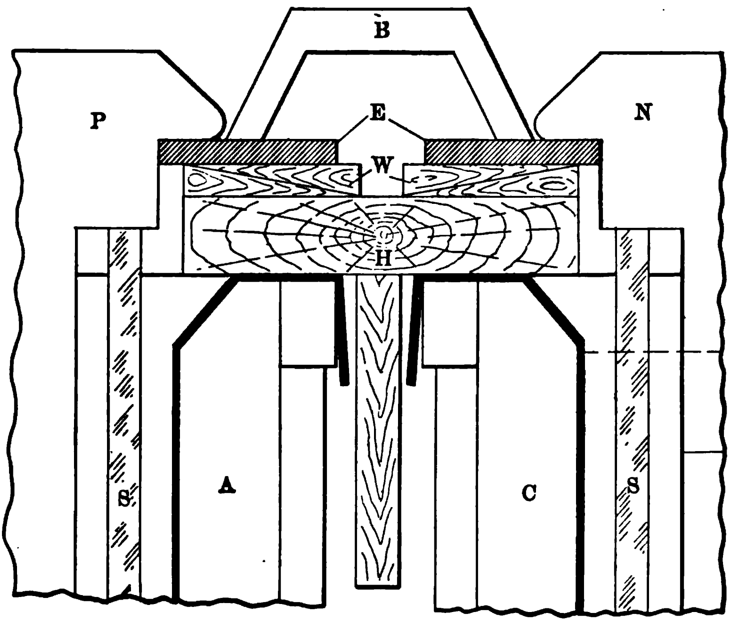


FIG. 118. Burning "Set-up."

wedges the level of the burning irons E, and consequently that of the bus bar B, may be adjusted so that the lower edges of the bus bar are exactly flush with those of the plate lugs.

The plates are burned to the bus bar with the assistance of special tongs, shown in Figs. 119 and 120. Figure 119 shows the tongs, bus bar and plates in elevation. Figure 120 is a plan. The tongs are beveled at the end to conform to the bevel of the bus bars, and the space between the two sides or "nippers" of the tongs, when they are closed, is just equal to the thickness of a plate. Lead is melted into the triangular space between plate lug and bus bar, the oxy-hydrogen flame being used. The lead is melted in gradually from the end of a bar, so that the joint is a complete weld.

The right-hand sides of Figs. 119 and 120 show plates welded to the bus bar, while the plates on the left hand are prepared for burning.

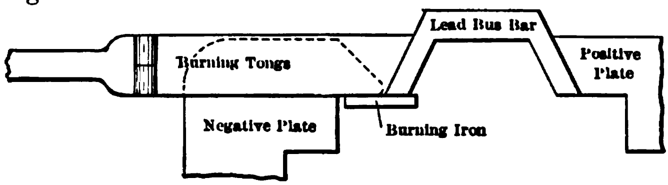


FIG. 119. Elevation of Burning Tongs and "Set-up."

Some makers have installed cells in which the tanks were placed close together, and each positive of one set of elements was joined directly to a negative of the adjacent set.

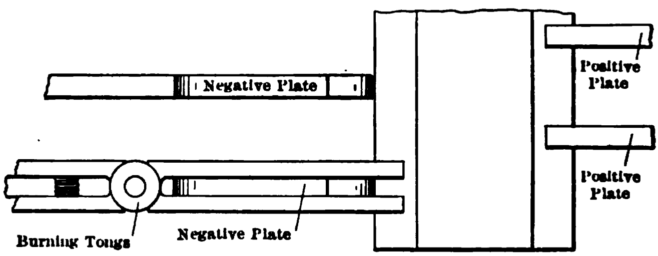


FIG. 120. Plan of Burning Tongs and "Set-up."

The cross section of the bus bars need not be great, as the distance that the current is carried is short, and the path is practically from plate to plate. Also, since conduction takes place *across* the bus bar from side to side, instead of along its length, the cross section available for conduction per plate is C, D (Fig. 117), multiplied by the length of the bar from the center of one plate to the center of the next.

When the last cell of a row is reached and the current is led to another row or to the switchboard, it must travel, at least for a short distance, along the length of the last bus bar, and in order to give it proper carrying capacity it is reinforced, as shown in Fig. 121. A copper strip is laid in the channel on the under side of the bar, and lead poured around it, the conductivity being increased thereby. In some cases, the copper bar is put into a mold, and the lead poured directly around it.

At points where the current is taken off, connection is made with a reinforced bus bar, by means of a lead covered copper connector which is joined to the copper reinforcing bar.

Figures 122, 123 and 124 show one of the methods of making this connection. The cable terminal (Fig. 124) is bolted to the upright copper bar or connector. In many cases the upright piece is cast solid with the reinforcing copper bar, and the joining of the two obviated.

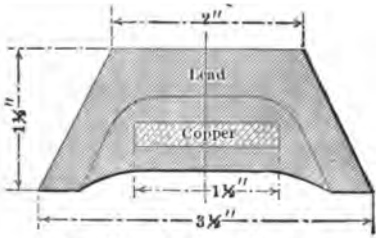


FIG. 121. Reinforced Bus-bar.

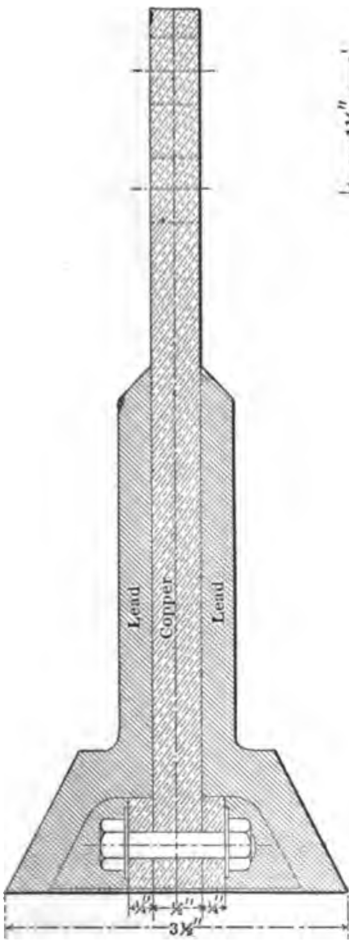


FIG. 122. Cross Section of Reinforced Bus-bar Terminal.

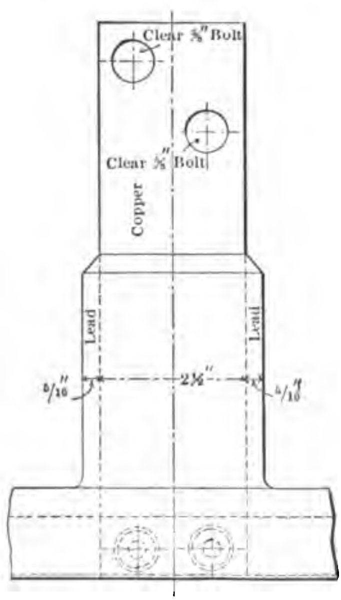


FIG. 123. Reinforced Bus-bar Terminal.

The room in which a storage battery is installed should be kept at a moderate temperature. It should be well ventilated, easily accessible, and the floor covered with brick or asphalt.

Cement floors are suitable only when kept clear of acid, as the action of sulphuric acid on even the best of cements is to dissolve them, and make them mushy and cause their final disintegration. Paraffined concrete, however, makes a very good floor.

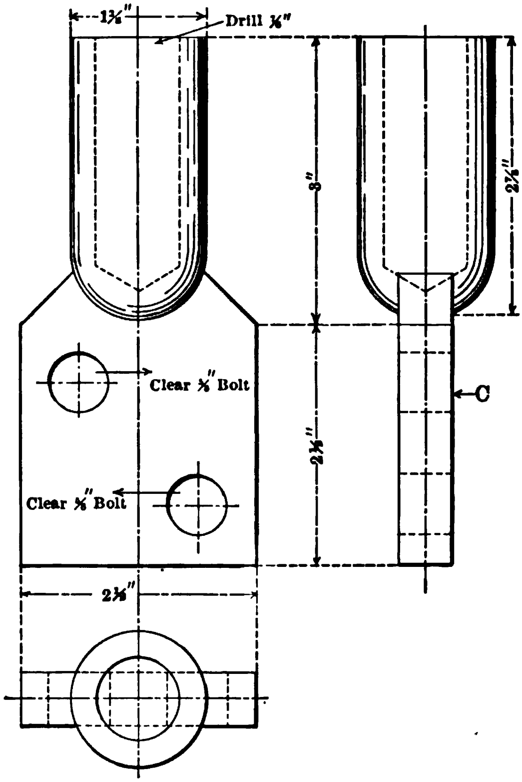


FIG. 124. Lug for Bus-bar Terminal.

Wooden floors have been used but their life is limited, as the acid from spray or leakage soon disintegrates the wood. If catch troughs of thin lead or asphalt be placed under each row of cells the greater portion of the released acid will be prevented from reaching and spreading over the wood, and the floor will last much longer than if these catch troughs be omitted.

The best, though a somewhat expensive, floor is made of concrete overlaid with a layer of sand about ½ inch thick, and on the sand is a covering of vitrified brick or tile set with wide joints which

latter are well grouted with tar or a high grade, pure asphalt, preferably asphalt.

Proper arrangements should be made for draining the battery room. Usually the floor is made to slope slightly from every direction downwards to a central point, at which an opening is made, connecting with a drain or sewer, the hole being covered with a cast-iron grating.

In large battery rooms several of these drains should be put in and the floor divided into sections, each sloped towards its drain.

The gases that form in a battery near the end of charge, together with the sulphuric acid vapors, make the atmosphere difficult to breathe and liable to injure any metal work in or near the battery. Therefore it is important that battery rooms be well ventilated, and usually it is necessary to employ for this purpose a small motor-driven ventilating fan, which continuously withdraws the acid vapors from the room. The ventilating system is always so arranged that the air from the battery room, with its corroding acid vapor, does not pass through the ventilating fan.

There are two methods of ventilation. In one, air is blown into the room and, by reason of the higher pressure thus produced,

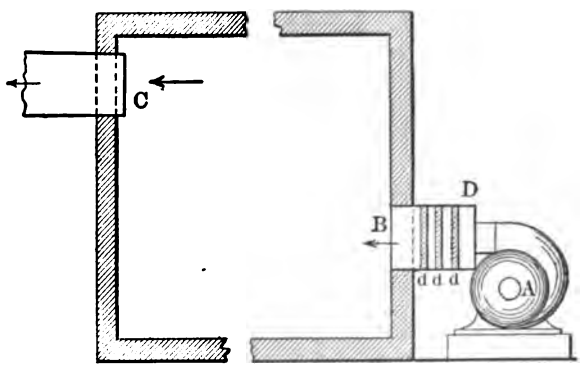


FIG. 125. Method of Ventilation for Battery Rooms.

the internal air passes out through an opening provided for the purpose. In the other, a current of air is blown through a pipe, and this air current produces a draft which draws air from the room.

Figure 125 shows diagrammatically the first described method. A is a blower driven by a motor, blowing air through screen box D and through opening B into the room. C is the exit for the outgoing air. d, d, d, are diaphragms of some open mesh cloth,

three in series, placed in the screen box between the fan and the room. The function of these diaphragms is to filter any dust or impurities out of the incoming air. They are placed in sliding frames which may be easily and quickly withdrawn and the fabric brushed clean.

In using this system the opening for the incoming air and that for the outgoing air must not be made near any battery cells, as the rush of air will take up so much of the electrolyte that the cells adjacent to these openings will either require careful daily attention, or they will be subject to the ills that attend on partially filled cells. The air must enter the room at some distance from the cells, spread evenly through the room, and make its exit at a point near which no cells are located. The openings should be located near the floor, as the acid vapors are much heavier than air.

The second method of ventilation is indicated diagrammatically in Fig. 126. The fan A drives air through the pipe E, the axis of

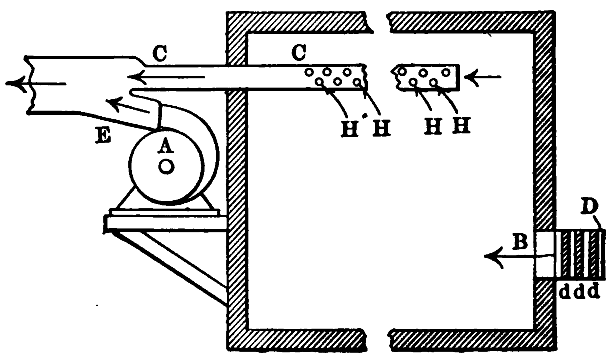


FIG. 126. Method of Ventilation for Battery Rooms.

which lies at a very acute angle with the axis of pipe C, which latter is within the battery room and has one end open inside the room while the other end projects through the wall and out into the atmosphere. Holes H, H, H are cut at intervals in the pipe C, as indicated.

When the current of air driven by the fan passes into tube E and outward through it into the external air, it draws with it, through the inner end of the tube C and the holes H, H, H, the air in the battery room. There must be an opening into the room to allow the ingress of fresh air. The air passing through this

opening should be screened, as indicated in the figure and above described.

The tubes may be of vitrified tile, sewer pipe, or wood lined with sheet lead.

Racks are heavy wooden frames or stands, on which the batteries rest, and, where floor space is limited, they are generally made to carry two tiers of cells, an upper and a lower.

Figure 127 shows a general form of construction which is strong and simple. The dimensions, of course, vary with the size

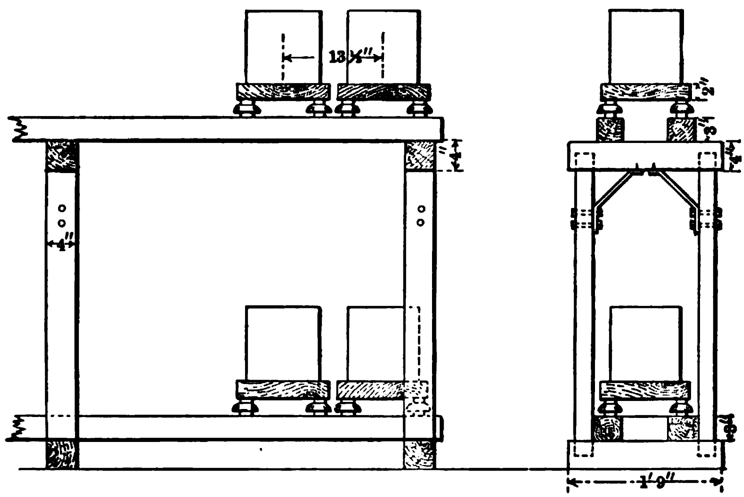


Fig. 127. Battery Rack.

of the cells. The method of making up this stand and the general proportions are obvious from the figure. In laying out a battery rack, it must be remembered that the weights supported are great, and the construction must be in accordance with this fact. The racks should be well painted with asphaltum paint to prevent the destruction of the wood by spraying acid.

Iron braces are sometimes used, but this is not advisable, as the acid leaking, or being thrown out with the ebullition of gas from the upper cells, will spread over the rack, and if it touches the iron will corrode it, and the iron salts formed would probably drip down into the cells beneath, or the gases from the lower cells would corrode the iron, making loose scales, which in time would fall into the lower cells. For these reasons iron racks are never used.

If any iron is used in the construction, it should be heavily coated with asphalt, or some equivalent protective covering. Racks should be set level, with the legs on vitrified brick. Some constructors put an insulator under each leg, the insulator resting in turn on a tile or vitrified brick.

Where large cells are installed, they are usually set on wooden stringers. These are elevated above the floor level by being set on insulators. Insulators are also placed between the cells and the stringers on which they rest, thus giving a double insulation from cell to floor.

The most recent practice is to sectionalize the stringers, making a pair just long enough to go under a single cell. With the double insulation and sectionalized stringers there is a quadruple insulation from one cell to any other cell, which is advantageous, especially in railway installations, where potential differences of 600 volts may exist between cells not very far apart.

Stringers, like racks and, in fact, all woodwork in a battery room, should be made of some resinous wood like yellow pine, thoroughly dried and heavily coated with asphaltum paint.

Individual cells must be well insulated to prevent leakage losses. Since the electrolyte often spatters out when the batteries are gassing, and is a good conductor, it is difficult to maintain a high degree of insulation.

The ordinary method is to rest each cell on four or more triple petticoat insulators — as indicated in Figs. 98, 99, 115 and 127

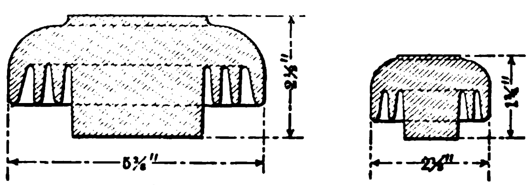


FIG. 128. Insulator.

(see insulators under containing cells). Figs. 128 and 129 show the types of insulators generally used. Glass insulators are superior to porcelain and should always be used.

To prevent the spread of electrolyte, which may have leaked or spattered out, and also to give an even distribution of the cell weight over the bottom of the jar, sand trays are used with glass containing cells. These are shallow trays made either of well-seasoned and paraffined wood, dovetailed and screwed together, or

of glass. They are about 1½ inches deep, and are filled with sand, and on this sand is placed the cell. The insulators are placed under the sand tray. The bedding of sand absorbs the lost electrolyte

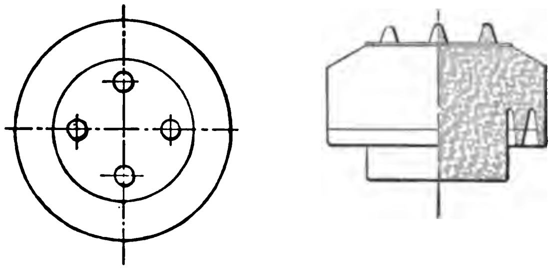


FIG 129. Insulator.

and prevents the electrical leakage which otherwise would occur. The sand should be of a good grade, perfectly dry, and preferably white silica sand, free from lumps and stone. Sawdust is a good substitute for sand and is frequently used. In Figs. 98, 114, 115 and 127 are shown sand trays underneath the glass jars, Fig. 114 showing a glass tray. Glass sand trays are more satisfactory and durable than wooden ones. They are usually made with bosses on the under side, on which they rest, and these serve both as supporting feet and insulators. No insulators, therefore, are required when glass sand trays are used.

Trays are not used with lead-lined tanks, these being placed directly on the stringers, with the insulators only underneath them.

In setting glass or rubber jars on the sand (or sawdust) in sand trays the sand must be gouged out of the middle of the tray so that the cell is supported around the edges and not on the central part of the bottom. If this precaution is not observed, "mysterious" breakages of glass cells will follow, due to the concentration of the weight on the bottom near its center.

After the installation is complete, test with a magneto for possible short circuits before pouring the electrolyte into the cells.

If the electrolyte is made by mixing acid and water at the point of installation, do this as directed in Chapter VI. A bottle of ammonia or some bicarbonate of soda should be kept on hand to neutralize acid which may be spilled on clothes.

The cells should be covered with a sheet of glass or other non-conducting, acid-resisting substance, laid on top of the plates so that all acid spray produced by gassing is arrested, and drips back

into the cell. Evaporation is also partially prevented. While not absolutely necessary, it is important that these cover sheets be put on.

In connecting up the cells be sure that the positives of one cell are connected to the negatives of the immediately adjoining cell, and that the positive and negative terminals of the charging dynamo are connected to the positive and negative terminals, respectively, of the battery.

If no instrument is available to show the polarity of the charging circuit, take two strips of bright lead and connect to the power circuit with an incandescent lamp in series with one of the strips. Immerse the two strips in a vessel of dilute sulphuric acid, keeping them well separated. In a few minutes a brown film will form on one of the strips, and this one is the positive side of the circuit. After the battery has been erected, prepare to give the initial charge. Do not pour in the electrolyte until all connections are made and the current is ready.

Start charge as soon as possible after pouring in electrolyte.

Never allow the battery to stand longer than two hours after the acid is put in, before starting the charge.

Charge at the normal rate as given for the particular battery by the manufacturers.

Continue the charge until the gravity of the solution and the voltage cease to rise. The charge should not be interrupted unless the temperature rises above 100 degrees F., in the event of which the current should be reduced to one-half the normal rate, and in case this is of no avail the charge should be discontinued and the battery allowed to cool, then charging should be resumed at half the normal rate for a few hours, when the current can be increased to the normal rate. The time for the initial charge is uncertain, taking from 36 to 60 or even 72 hours. Its duration must be governed entirely by the conditions above mentioned as to gravity and voltage.

At the end of charge adjust specific gravity of the solution to the standard strength S. G. 1.200, and its height above the top of the plates to the standard level of 1 inch.

After the initial charge, the battery can be put into service, although it is better to discharge it about one-half, at the normal rate, and then immediately to recharge it, before putting into regular use.

CHAPTER XXI.

DURABILITY AND CAUSES OF DETERIORATION.

The portions of a battery installation subject to injury or depreciation are:

(1) Stringers or racks.
(2) Insulators.
(3) Sand trays (if used).
(4) Containing cells.
(5) Electrolyte.
(6) Positive plates.
(7) Negative plates.
(8) Separators.
(9) Bus bars and connectors.

If the stringers or racks are of thoroughly dried wood, well filled with asphaltum paint and kept reasonably clear of acid spray, they will last for many years. If not well painted, however, and if covered with a film of acid, they soon are eaten away and have to be replaced. The attendant cost is far beyond that of the stringers themselves, as the changing of supports under heavy loads such as battery cells is expensive under ordinary conditions, and when extreme care has to be used as well not to break the plates, connections, or tank linings, the cost is relatively very great. All woodwork, therefore, must be kept dry.

In this connection, the approximate comparative costs of different items entering into the cost of a battery installation may here be given. They are: positive plates, 32%; negative plates, 22%; lead-lined wood tanks, 12%; acid, 3%; racks, insulators, connectors, etc., 12%; work of installation, 19%.

Insulators are permanent if properly selected and not subjected to any blows or impact from setting tanks on them, or by such external causes as blasting in the neighborhood. The size and number under each cell should be such that no excessive compression strains are produced.

Sand trays, when of wood, are subject to the same kind of

deterioration as rack and stringers. Therefore the same precautions as to painting and dryness apply.

Glass sand trays are permanent unless broken by shock or too rapid changes in temperature.

Containing cells. It is particularly important that these be preserved against injury, as there placement of large-sized ones means not only the cost of the new tanks but the expense of cutting out plates, and subsequent re-erection. Also if the plates have been in service for a long period, the handling, in removal, may injure them so that new elements will be required, the effect being to reduce the length of service of the plates. In nearly every instance the separators will have to be replaced with new ones. The durability of lead-lined tanks depends on:

(*a*) Thorough painting of wood inside and out at time of construction.

(*b*) Secure, first-class lead burning at all joints.

(*c*) Proper thickness of lead lining.

(*d*) Insulation from stringers and adjacent tanks.

(*e*) Dryness of tanks, insulators and stringers.

(*f*) Absolute separation of plates from lining.

If there is any leakage of current through the lead lining, it will become pitted, and soon small perforations will be produced.

Absolute insulation of every tank from its neighbors and from the stringers is necessary to avoid this trouble. Acid spray forming a film over the surface of tanks and insulators provides a path for current leakage. It also finds its way into fine joints, cracks or other openings and eats away the wood. Glass sheets used as covers over the tops of the cells will prevent most of the acid spray from leaving the cells, and should, in most cases, be put in place.

A wet battery room means the rapid depreciation of nearly every part of the installation.

The electrolyte requires but little acid renewal, and the amount used in a year represents an insignificant cost. Considerable distilled water must be used, however, to replace that lost by evaporation, electrolytic dissociation, and that lost as spray.

The separators will last just as long as the plates are undisturbed, but whenever the elements are removed from the cells new separators generally have to be put in when the elements are reassembled, unless the separators are only a few months

old. This applies to wood separators. Glass rods are permanent unless accidentally broken.

The bus bars and connectors may be considered as permanent if the parts of copper or iron are well coated with asphaltum paint and the battery room is kept dry and well ventilated.

The durability of battery electrodes is dependent on:

(1) Character of
(2) Adhesiveness to supporting grid of
(3) Means for holding to grid of (pasted plates)
(4) Thickness of layer of
(5) Porosity of
(6) Distribution over supporting plate surface of
} active material.

(7) Density
(8) Quantity
(9) Purity
} of electrolyte.

(10) Rate of charge per unit of plate area.
(11) Rate of discharge per unit of plate area.
(12) Duration of maximum rates.
(13) Maximum voltage to which cells are charged.
(14) Minimum voltage to which cells are allowed to discharge.
(15) Time elapsing between the cycles of charge and discharge.
(16) Maximum temperature at which cells are operated.
(17) Maximum length of time cells are permitted to stand idle in electrolyte.
(18) Efficiency of separation between plates.
(19) Freedom from conditions favorable to local action.
(20) Location with reference to gases which might be absorbed in the electrolyte and prove injurious to the plates.
(21) Amount of available base lead on the peroxide elements which may be converted into active material (in Planté plates).

In previous discussions, most of the characteristics enumerated and their effects on the general working of batteries have been considered. This chapter, therefore, is practically a recapitulation of preceding observations, collated with reference to their effect on the life of the plates.

(1) The character of the active material which is best suited to produce long life is hard and tough, yet porous and of low specific

gravity. The coherence between the particles should be of a high order, and the whole should be a strong, compacted mass, hard like soapstone, in the case of the peroxide element, resisting the thumb nail, while the spongy lead element should be soft and easily pressed into by the nail. Such materials can expand and contract without shedding or dropping particles from the surface.

(2) The material must also be firmly attached or held to the support plate or grid. Otherwise, parts may shed or peel off, no matter how coherent the active material itself may be. Poor contact, also, allows gradual sulphation of active material, as it is not thoroughly traversed by the charging current and changed back to its proper state, Pb or PbO_2. Furthermore, with a pasted plate there is always the possibility of a layer of sulphate forming between the grid and the active material.

(3) The efficiency of an envelope, where one is used with pasted plates, affects the durability, as is obvious.

(4) The thickness of the layer of active material is also a factor and it should depend on the service the battery is to perform. Since expansion occurs on discharge and contraction on charge, there is always a tendency to break off the active material or to distort the plate itself if this expansion be too great. Therefore, for a given quantity of active material the thicker the layer, the less the exposed area will be for a given quantity of active material and the surface expansion will be less for a given ampere hour discharge. If, however, the layer be too thick, the capacity at high discharge rates is lowered, and other considerations require that the layer be thin where the battery is to charge or discharge at rapid rates. Only in batteries that operate under moderate rates of current flow should the layer be thick.

The life of a positive plate is limited chiefly by the shedding of the lead peroxide, which loss of active material is inseparable from the working of storage cells.

The increase in the volume of active material on discharge is considerable, and with a hard, unyielding material, such as lead peroxide, any changes in volume, repeatedly produced, must result in the cracking loose of particles from its mass and from the supporting grid. Also on high discharge rates that portion of the layer furthest from the grid is more completely reduced to $PbSO_4$ than the portion in contact with the grid, because the electrolyte is in contact with the surface of the plate, but to reach

the interior of the active mass, it must diffuse through the pores of the material, which diffusion cannot take place freely through a thick layer. The outer surface of the layer, therefore, expands more than does the inner portion. This inequality of expansion causes a rapid shedding of the lead peroxide. Therefore if the plates be subjected to rapid discharge, a thick layer will shed faster than a thin one: the converse condition obtaining if the discharge rate is low and prolonged until the cell is completely discharged.

The sponge lead on the negative electrodes also expands when changed into lead sulphate, but the material being soft and spongy can change its volume easily without shedding.

(5) The greater the porosity, the more accessible is each particle of active material to the electrolyte, and the more complete and uniform the chemical action; also the expansion tending to distort the plate will be less, as the pores leave some space which allows the molecules to increase their volumes: in other words, the material becomes more dense on discharge.

(6) The distribution of the active material over the support plate has a most important bearing in that unequal distribution or unequal densities or unequal contact with the grid at different points on the surface will result in unequal distribution of current. This causes unequal expansion of the different parts of the same plate and allows some of the active material to become overcharged from excess of current flow through it, while other parts are undercharged. The charge tends to equalize itself over all the active material after the battery has stood for a short time with current cut off, but before this equalizing takes place, and during it, conditions are favorable for local action.

(7) If the density of the electrolyte be too high, there is danger of sulphation of the negative plates.

Pfaff has made some experiments on the influence of acid concentration.* He found the positive plates were affected only slightly by changes in electrolyte density. High electrolyte densities, however, are ruinous to the negatives, as has been explained in Chapters VI and X.

(8) If there is not enough electrolyte in the cell, the density toward the end of discharge — especially in the pores of the plates — becomes low and the acid is highly diluted. This leads

* Centralblatt für Akkumulatoren, Vol. II, pp. 73 and 173.

to concentration currents and consequent partial sulphation of the electrodes. Also the electrolytic decomposition of highly dilute acid appears to have a deleterious corrosive effect on the elements, which shortens their life.

(9) The effects of impurities in electrolyte are, generally, to corrode and eventually disintegrate the plates, to fill up the pores and decrease their capacity, or to cause local action by deposition on the plates and producing with the active material on which it may be deposited, a couple, which causes local action.

If the impurities are lead-attacking acids or their salts, the rapidity of shedding of the positive active material is increased and in Planté plates the underlying base lead is more rapidly attacked.

(10) Moderate rates of charge and discharge allow the concentration changes of the electrolyte in the pores of the active material to take place gradually, the rate of diffusion being as rapid as the concentration changes, and thereby more nearly equalizing the charge throughout the mass of the material. Also the contraction in volume of the active material takes place so slowly that the lead peroxide does not crack or shed so much as when the charge rate is high.

High charge rates throw off a greater amount of lead peroxide than do low rates, not only because of the rapid change in volume mentioned, but due also to the rapid evolution of gas within the pores of the plate, which forces its way through the material and carries off small particles with it.

High charge rates may produce an unequal rate of conversion of the active materials in parts of the same plate, and the unequal stresses set up by the volumetric changes will cause distortion or "buckling" of the plate.

Extremely low rates of charge will cause Planté positive plates to sulphate. The charging current for Planté positive plates must not be less than the 16-hour rate, as lower discharge rates will cause buckling or cracking of the plates and excessive corrosion of the underlying base lead. This is due to the fact that the potential difference between the plate and the electrolyte is below the critical potential difference as explained in Chapter III, and a rapid formation of sulphate from the base lead takes place. Plates having provision for expansion will not be distorted, but in any case the lead is corroded and the durability of the plate reduced.

(11) Moderate rates of discharge are desirable, just as moderate rates of charge are, and for practically the same reasons. Rapid charge is more harmful, however, than rapid discharge, owing to the fact that the material in the former case is contracting, and if the change takes place too rapidly may pull loose from the grid, and this tendency is augmented by the evolution of gases.

Jumau has made a study of the loss of active material from several types of plates, his observations extending over a long period of time.

He found that the amount of lead peroxide released from the grid and deposited in the bottom of the cell is a function of the ampere hours discharged and is affected but little by the rate at which the discharges take place.

The curves shown in Fig. 130 indicate the amount of deposit taken from the cell from a given number of discharges. About

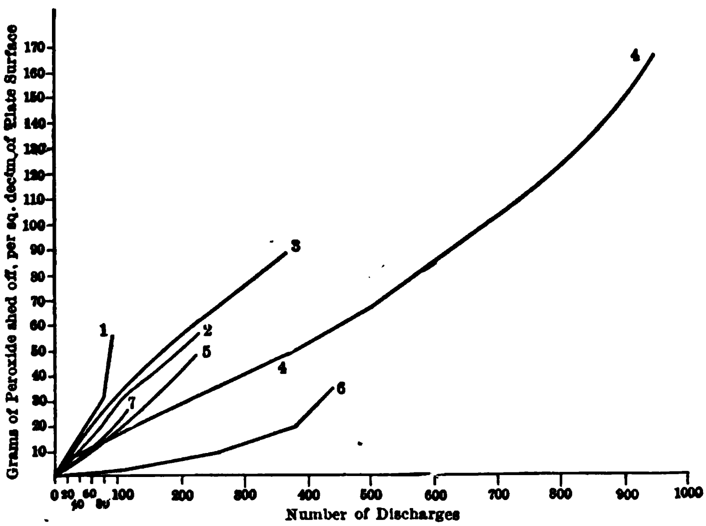


FIG. 130. Shedding of PbO_2, with Number of Discharges

50% of this deposit is sulphate. By experiment, 0.88 gram of PbO_2 will give 1 gram of deposit. Therefore the figures representing the ordinates of the curves should be multiplied by 0.88 to give the actual weight of PbO_2 released from the plates.

The kinds of plates, change in capacity, rates of charge and discharge, number of discharges and deposit per ampere hour are given in the table herewith.

TABLE XIX.

No. of curve in fig.	Type of plate.	Periods of discharge.	Least specific capacity in amp. hrs. per sq. dm.	Amps. per sq. dm. discharge.	Loss of peroxide, grams per amp. hr.	No. of discharges to end life.	Average deposit, grams per amp. hr.
1	Pasted ..	0-50	5.88	0.775	0.068	75	0.068
		50-75	5.94	0.775	0.067		
		75-93	3.00	0.775	0.500		
2	Pasted ..	0-50	3.80	1.030	0.068	230	0.073
		50-100	3.55	1.030	0.087		
		100-200	3.25	1.030	0.068		
		200-230	3.00	1.030	0.072		
3	Mixed...	0-50	4.00	6.80	0.090	370	0.053
		50-100	4.05		0.067		
		100-200	4.40		0.051		
		200-300	4.90		0.044		
		300-370	5.00		0.037		
4	Mixed...	0-50	2.15	6.80	0.091	945	0.043
		50-100	2.25		0.059		
		100-200	2.50		0.046		
		200-300	2.90		0.040		
		300-400	3.60		0.037		
		400-500	4.20		0.034		
		500-600	4.75		0.040		
		600-700	5.38		0.035		
		700-800	5.65		0.032		
		800-900	5.10		0.053		
		900-945	4.15		0.086		
5	Pasted ..	0-50	2.28	1.030	0.070	230	0.090
		50-100	2.32		0.095		
		100-200	2.38		0.097		
		200-230	2.62		0.039		
6	Planté...	0-50	0.50	0.113	0.023	444	0.036
		50-100	1.25	0.227	0.016		
		100-200	1.88	0.453	0.026		
		200-300	2.40	0.453	0.026		
		300-400	3.25	0.453	0.036		
		400-444	3.20	0.453	0.072		
7	Planté...	0-50	3.80	1.225	0.050	115	0.066
		50-115	2.88		0.083		

The following results are particularly notable. The loss of peroxide is far less in the case of Planté plates than with the pasted type, while the mixed variety (*i.e.*, pasted plates having soft lead grids which may be coated with peroxide and form base lead,

from which peroxide may be produced as the pasted material falls away) lies between the Planté and the pasted types. The Planté plates last through a larger number of discharges at rapid rates than at slow rates. This is due to the fact that the number of ampere hours is less for a high rate than for a low rate, and the loss is more nearly proportional to the ampere hours than to the number of discharges. The loss of material per ampere hour is, however, higher at high than at low rates. In some cases doubling the rate will increase the loss of peroxide per ampere hour over 30%.

Rapid discharge may also produce peroxide on the negative plate by reason of the copious release of oxygen and other products of electrolysis. The final result would be local action.

(12) From (10) and (11) it follows that the bad effects due to high current rates are proportional to the times during which they continue.

(13) While it is occasionally advisable — say once a month — to charge the batteries up to about 2.60 volts per cell, this would be harmful if done continuously, because the gases formed inside the pores are liable to crack or peel off the active material in forcing their way out. They also may force themselves between the active material and the grid, thus decreasing the contact between the two and paving the way for troubles from sulphation by secondary action.

The active material is also liable to break or "shed," because its volume changes greatly, owing to the complete reduction of sulphate. It is, however, well to overcharge several times each year in order to completely convert the sulphate which may have accumulated, into peroxide. Some manufacturers advise that this overcharge be given weekly.

(14) The minimum voltage to which a battery is permitted to discharge is probably the most important of all the factors which affect durability. If the discharge be carried too far, over-sulphation, dangerously great change in volume of active material, resulting in fracture, shedding or buckling, excessive dilution of acid in pores, resulting in local sulphation, are the possible consequences.

(15) If considerable time elapses between the end of discharge and the beginning of charge, sulphation invariably occurs. Cells which are fully charged, and which are allowed to stand idle for any considerable length of time, will discharge themselves by leakage

and local action, and the active material gradually becomes sulphated.

The sooner a battery can be charged after the end of discharge, the more satisfactory will be its operation and the longer its life.

(16) The maximum temperature at which a battery is operated should not exceed 90 degrees F., and certainly not be greater than 100 degrees. Pasted electrodes are injured less than Planté plate, under high temperatures. At high temperature the chemical activity is more rapid, the pores more open, and tendency to sulphation therefore greater than at lower temperatures.

(17) If the plates are not efficiently separated, and leakage or short circuits can form from one plate to the one adjacent, obviously the conditions for internal discharge and ultimate sulphation will be present.

(18) If batteries be located where fumes or gases which carry lead-attacking elements, may be absorbed by the electrolyte, and afterwards travel from the anode to cathode, and back again, as charge and discharge take place, the probability is that the plates will finally be disintegrated. This is a condition which might easily obtain in a chemical works and plants of a like character. This is particularly true of ammonia, which may be absorbed if a battery is installed near refrigerating plants or stables.

(19) In Planté plates, the life of the positive elements is dependent largely on the amount of lead in the plate, available for conversion into active material. As the peroxide coating sheds, the action of the charging current converts the exposed lead left into peroxide, and in this way the plate is being continuously re-vitalized. The usefulness of the plate is ended when the available lead is completely used up. Planté plates having thick ribs are therefore more durable than those having thin ones, though this durability is obtained at the expense of a reduction in capacity, as a plate having a number of thin ribs has a greater capacity than one of the same size but having a smaller number of thick ribs.

Usually the positive plates next to the outside negatives, disintegrate before the other positives show signs of serious depreciation, because they are more active and give more than their proportional amount of current on discharge. This is due to the fact that the current flow from the outside negatives is less than from the other negatives because only one side is active. The potential drop through the grid is therefore less, and in the

tendency to equalize the drop between different plates the outer negatives supply more current than they should, and cause an excess of current flow in the adjacent positive plates.

In connection with the question of durability a test made in 1902 by the French Admiralty is of interest. The conditions of the test were that no cell weighing above 225 kilograms (500 lbs.) could compete. Each cell was required to stand charge at the rate of 330 amperes, and each charge was to exceed the discharge in ampere hours by 50%. The rate of discharge was 600 amperes, the final voltage 1.65 at this discharge rate which must last at least half an hour. 21 cells were submitted, and after 250 discharges, only 5 cells were capable of discharging at the specified rate for half an hour. Of these five the best four were exclusively pasted electrodes, and the best cell (a Heinz) weighed only 181 kilograms (403 lbs.), of which 106 kilograms (357 lbs.) represented the weight of the electrodes.

CHAPTER XXII.

DISEASES AND THEIR REMEDIES.

FROM the enumeration of conditions for durability, it can be seen that most troubles are the results of failure to observe the requirements cited.

The principal diseases to which a battery is subject are:

(1) Loss of capacity.
(2) Corrosion of plates.
(3) Fracture and buckling.
(4) Shedding of active material.
(5) Sulphation.
(6) Reversal of negative plates.
(7) Internal discharge.
(8) Hardening of negatives in air.
(9) Loss of voltage.
(10) Softening of peroxide (on pasted positive plates).

(1) Loss of capacity — as distinguished from loss of charge — may arise from (a) clogging of pores of the lead sponge with sulphate or impurities; (b) contraction of the pores of the mass; (c) loss of active material from the grid; (d) formation of a layer of sulphate between the grid and the active material; (e) loss of electrolyte.

When the negative plate shows a decreased capacity, and exhibits no sign of sulphation or loss of material, it will generally be found that the material has shrunken, or the pores are clogged with sulphate and impurities.

The rejuvenation of these plates is accomplished by charging the battery, removing the negative elements, placing them in a bath of sulphuric acid as cold as possible and having a density of 1.240. They are connected as anodes, or in a reverse manner to that in which they are normally connected. As cathodes, "dummy" plates of plain sheet lead about $\frac{1}{16}$ inch thick are used. On passing current through the plates, the sponge-lead is converted into PbO_2. When the active material is completely per-

oxidized, the current is again reversed, the acid in the bath first being removed and fresh acid substituted in order that the impurities may not be redeposited on the negative plates. When the elements are finally converted back into sponge-lead and reassembled with the positives, it will be found that the capacity and activity of the battery are increased and brought up to nearly their original condition. Reversal of the complete battery — both positives and negatives — should be avoided if dummies can possibly be secured. If not, however, and the reversing be carefully done, possibly no harm will result to the positive plates.

The rate of current flow on reversal and the subsequent change back to sponge-lead should be high so that the changes are rapidly passed through, thus avoiding the danger of sulphating. The 3-hour current rate should be used until the plates become brown and gas vigorously. The current should then be gradually reduced to the 8-hour rate. The charge should be continued until a condition is reached where, if the current be stopped for one-half hour, and then turned on again, gassing immediately begins. Be sure before allowing to stand on open circuit that all sponge-lead is converted to PbO_2, otherwise a heavy internal discharge will result. If the temperature rises above 70 degrees F., the plates will disintegrate and be ruined.

The reversal of the plates back to sponge-lead must be done in the same manner as the first reversal. After the plates have been brought back to sponge-lead a prolonged charge at about one-half the 8-hour rate should be given them. The acid in which the change from sponge-lead to peroxide takes place should not be used as electrolyte until the impurities discharged by the plates are removed.

Loss of electrolyte by evaporation should be made up by proper addition of pure, distilled water. If the liquid does not completely cover the plates a smaller active surface is exposed, and the capacity proportionally decreased.

(2) Corrosion of plates may occur from two causes: (a) the chemical action resulting from electrolytic decomposition of highly dilute acid in the pores of the active material, and (b) the presence of lead-dissolving acids or their salts in the electrolyte.

The first condition cannot be remedied, as it occurs in every cell if the discharge be pushed too far, or if the plates have a thick layer of active material when the rate of discharge is high. If the

electrolyte contains lead-dissolving acids, their presence will be manifested by a continuous increase of capacity, which means that the forming process still goes on attacking the plates. The obvious remedy is to change the electrolyte, and substitute fresh acid, free from injurious substances. In addition to these effects, there is the normal slow disintegration due to the action of the acid and products of decomposition, which cannot be completely stopped, as it is the natural depreciation to which plates are subject. It can be partly remedied, however, by decreasing the density of the electrolyte. The best density for positive plates is 1.230, and for negatives is 1.190 (approx.); 1.210 to 1.220 is the usual density, being a compromise between the two.

All corrosive actions of liquids on solid substances immersed in them take place with greatest rapidity at the surface of the liquid, and the portions of the battery plates which emerge from the electrolyte may disintegrate at the surface of the acid before the submerged portions have greatly depreciated. This can be rendered of small importance by keeping the plates always completely covered with liquid, and making the lugs which pass from the plates out to the terminals, of thick dense lead.

(3) Fracture and buckling are due to excessive or unequal expansion, usually the latter. They indicate that the discharge has been carried too far, the rate of charge or discharge has been too rapid, or that the current distribution over the plate was not uniform, and certain portions were too far or too rapidly discharged. With certain types of Planté positive plates, a very low charging rate will cause buckling, as explained in the previous chapter and Chapter III. Buckling can take place even at normal current rates if the formation of active material or its application be not uniform over the exposed surface. Should buckling occur under these conditions, it would indicate a defective plate.

Buckling on discharge seldom if ever takes place. On very rapid rates of discharge it might be caused by a slight inequality of distribution of active material, together with differences in electrolyte densities which occur at different levels in deep tanks. Batteries which are discharged at a high temperature may also buckle, due to the increased capacity and consequent additional formation of sulphate, thereby changing the bulk of the active material more than if the discharge had taken place at a lower temperature, and less capacity had been delivered.

A phenomenon observed by Sir David Salomans, and yet unexplained, is the buckling of plates exposed to light, the convex side always being away from the light.

It is probable that any portion of a plate exposed to light receives also some heat. This would make the warm portion deliver a greater amount of energy on discharge than would the other portions at some lower temperature, resulting in the unequal expansion of the active material and consequent plate distortion.

If the troubles arise from defective plates, there is no remedy save to keep the electrolyte circulating, refrain from discharging too far, and keep excluded from light and heat.

(4) Shedding of active material cannot be prevented if it be improperly formed or applied, and is of such a character that it easily disintegrates or loosens from the grid. Shedding occurs with good active material, however, to a limited extent, and this is due to expansion and contraction, which the grid cannot follow, or to the rapid release of gases when charging is done at high rates or the plates are overcharged. When shedding takes place in a greater degree than ordinary usage and depreciation call for, the following rules should be observed:

Charge at lower rates; do not overcharge, *i.e.*, do not go above 2.4 volts; do not discharge down too far, say below 1.8 volts. Pasted plates should not be charged after gassing begins, except on a monthly overcharge.

(5) Sulphation of the injurious kind differs from the normal sulphation of charge and discharge, in that it is almost irreducible, causes shedding of active material, buckling, loss of capacity, increase of internal resistance with consequent reduction of efficiency, and increase of temperature with passage of current.

The causes of over-sulphation are over-discharge, either of the entire mass of active material or only certain portions of it, or standing discharged. The injurious effects are those which arise from great increase in resistance and excessive expansion and contraction, which are mentioned above.

The causes of over-discharge are: (a) intentional, through external circuit; (b) local action and leakage; (c) loosening of active material, which reduces the capacity of a plate and normal discharge therefore over-discharges it; (d) short circuits between plates.

Excessive discharge rates, if prolonged, tend to form a surface layer of sulphate, which prevents the inner portions of the active mass from participating in discharge and thereby causes the action to take place on the small portion forming the outer layer, which results in over-discharge of the surface and formation of the non-reducible sulphate.

When the active material is not in close contact with the grid, and the electrolyte is able to penetrate between the two, it is evident that on discharge the action will take place most rapidly on that portion of the active material nearest to the grid, and a layer of sulphate will be formed on this surface. When the sponge-lead or peroxide is sufficiently reduced, the layer of sulphate between the grid and the active mass becomes non-conducting, and current cannot be forced through the plates, except at a high voltage. If the acid density or the temperature be high the process of sulphation is augmented. This is a rare occurrence and can only happen with pasted plates.

In addition to these injurious effects, those previously mentioned, due to change of the volume of the active material, are usually present. Cracking and shedding of active material, and buckling, generally result.

Local action will cause over-discharge and consequent sulphation, as will also short circuits between the positive and negative elements.

Although sulphate is white, the first manifestation of its presence is through the gradual darkening in color of the negatives. If the process continues, eventually flakes of white, pure sulphate will form over the plates or the portions that are affected. Where the sulphate forms in small white patches which lie only on the surface of the plate, and does not penetrate into the pores of the active material, it is harmless. In this case, rubbing the plate slightly with a stick will cause the sulphate to fall off and disclose healthy active material underneath. Sulphated plates are those in which the sulphate has penetrated into the pores of the active material. The best treatment for sulphated plates is to convert them to PbO_2 or Pb under high current densities. The author has found that if the sulphation has proceeded very far, the heating of the cells, due to high resistance, limits the rate of the current flow. The charging rate should be determined by the thermometer, and should be as high as possible, with the tem-

perature not to exceed 105 degrees F. Usually at the beginning of charge the current which will produce this temperature is very small, and rapid initial rates are not possible, though the current can be increased as the reduction of sulphate proceeds.

Plates which have a layer of sulphate between the grid and the active material are usually not reducible, and must be renewed and replaced by others. Sometimes, however, if the layer is not too thick, or completely turned to sulphate, the reduction may be effected. If the sulphating action has gone so far that the plates have lost capacity, the plates should be taken apart, and the positives and negatives separately connected up with dummies, and current passed through in the proper direction (positives as anodes, negatives as cathodes), to reduce the sulphate. If sulphation is produced by local action, the causes thereof should be investigated and removed (Chapter X).

The density of electrolyte and the temperature should also be within the prescribed limits. While neither of these factors causes sulphation, they greatly assist the real causes and accelerate and augment this injurious action.

Short circuits should be prevented by keeping the cells cleaned out and never allowing the sediment — which is a conductor — to accumulate in the bottom or between the plates on the separators. Also, the separators and spacing of the plates should be given occasional attention.

When an excess of sulphate once forms, several cycles of charge and discharge are necessary to bring up the battery to its normal capacity. The first charge should always be a prolonged overcharge. When large cells are connected up in series, and it becomes necessary to charge a single cell sufficiently to bring it up to proper condition, without subjecting all the other cells to an injurious overcharge, it is usually done by cutting out the defective cell and arranging short lengths of wire or cable — called "jumpers" — so that the cell may be connected in circuit with the others on charge, and cut out on discharge, the current being passed around the defective cell by means of a "jumper." A repetition of this process will finally produce the desired overcharge.

If the cell has to be brought up to condition quickly, it may be connected in with the others on charge in the regular way, and in a reverse direction on discharge, so that the discharging current

of the system passes through the defective cell as charging current. The process is in this way continuous, but it is awkward to handle the large "jumpers" and contacts that are required for large cells, and the application is therefore limited to the small sizes of cells. Furthermore, the cutting out of a cell decreases the voltage of the system two volts, and if it be cut in on discharge in a reverse direction, the drop through it will be about 2.5 volts, making 4.5 volts lower electro-motive force on the system. The service, therefore, must be such as to admit of this drop, or the end cells or booster must be able to compensate for it.

This method is of course impractical for large installations where the plates are "burned" to bus bars.

A convenient way to charge a sulphated cell without cutting it out of circuit is to use an auxiliary dynamo, its application being particularly suited to plants having boosters.

The potential required to charge a sulphated cell is under 3 volts, and to obtain this low potential at the dynamo brushes, it is necessary to reduce the field strength of the machine. This is effected by disconnecting the dynamo fields and joining one of the field terminals to the extreme cell of the series, at the end, where the end cell switch connections are made. The other terminal is connected to the end cell switch contact. In this way one or more cells may be connected across the field terminals, the number varying with movement of the end cell switch.

With this low potential excitation, which may be adjusted to suit the purpose by shifting the end cell switch or the field rheostat, the generator voltage may be fixed at exactly the desired value.

A pair of cables leading from the generator brushes to the terminals or bus bars of the defective cell and attached thereto, the positive pole of the dynamo being connected to the positive battery bar and the negative from the dynamo being joined to the negative of the cell, completes the arrangement. A constant charge, which is independent of the charge and discharge currents flowing through the cell, may now be sent continuously through it. Before switching current from the dynamo to the cell, test the dynamo voltage to make sure that a potential is being produced. If by reason of faulty connections there were no dynamo potential, the cell would be short-circuited through the armature, further injuring the cell and probably burning out the dynamo. Large

installations are generally provided with special boosters — called " milkers " — for charging single sulphated cells.

(6) Reversal of negative plates occurs only when there are several cells in series with each other or some external electromotive force, and is occasioned by complete discharge down to zero and continued charge in a reverse direction, with a consequent reversal of the plates. This seldom happens, however, except in cases where a cell loses its capacity through some accident or defect and its discharge is ended before the other cells in series with it have been completely discharged. The large capacity cells overpower the defective cell and reverse it. The remedy is to recharge and to continue the charge until the cell is brought fully up to its normal condition. The cause of the capacity loss should be ascertained and corrected, otherwise the reversal will again take place on the next discharge.

To overcharge a battery in series with other cells, the method of connecting in on charge and cutting out on discharge, or a low potential generator, as described in the preceding paragraph, may be employed.

(7) Dr. F. Peters * shows that the active material on pasted positive plates softens, owing to the expansion and contraction on discharge and the action of escaping bubbles of oxygen formed on charge. This action loosens the particles on the surface of the plate and destroys the cohesion between the particles; also they do not reduce back to PbO_2 (except partially), and therefore do not harden again. The acid mixes with these separated particles and produces the well-known soft, mushy substance which in course of time is the condition of the entire mass, the effect described extending gradually through the whole thickness of the electrode.

No change in the chemical composition of the active material due to the softening process is discoverable.

Plates in this condition may be again brought to their healthy condition of hard PbO_2 by discharging, reversing and forming to sponge-lead, thereby causing a contraction of the active material and a firm cohesion of the various particles. Afterwards the electrodes are again reversed and changed back to PbO_2. The expansion of the particles fills up most of the pores, and as all the active mass is fully reduced to PbO_2, the plate regains its hardness.

* Centralblatt für Akkumulatoren, May, 1900.

Some of the outer layer of active material will come off in the process, but usually the amount so lost is small, and if the reversal is carefully done the results more than counterbalance the insignificant loss of peroxide.

The reversal should be done at high current rates, as described in paragraph 1.

CHAPTER XXIII.

CARE AND MANAGEMENT.

In addition to the foregoing discussions, there are a few points concerning the operation of batteries which should be noted.

On continuous discharge the one-hour rate should usually not be exceeded, and this should last only a short time, say twenty minutes, except in occasional emergencies or in the case of regulating batteries, where the twenty-minute rate may be allowed for a minute or two when the load fluctuations are very great. The circuit breakers should be set for three times the one-hour rate. When discharging at the normal rate, the discharge should never be allowed to continue below a voltage of 1.75 volts per cell. At rapid rates the discharge may be carried down to 1.60 volts per cell. If discharge be continued after these voltages are reached, the plates will be injured.

The rate of charge may be rapid when the battery is nearly or quite exhausted, but should be low when nearing the end of charge, that is, after the evolution of gas begins.

Good rules for charging cells that have pasted plate elements are as follows:

TABLE XX.

To charge in 8 hours,	40 per	cent	of	total	charge	first 2 hours
	30 "	"	"	"	"	second 2 hours
	20 "	"	"	"	"	third 2 hours
	10 "	"	"	"	"	fourth 2 hours
To charge in 5 hours,	30 "	"	"	"	"	first hour
	25 "	"	"	"	"	second hour
	20 "	"	"	"	"	third hour
	15 "	"	"	"	"	fourth hour
	10 "	"	"	"	"	fifth

To charge in 4 hours, 35% of total the first hour; 52% the next two hours, and 13% the fourth hour. The above figures apply only to cells that have been completely discharged.

Take occasional voltage readings of each cell to keep informed

as to the performance of the separate cells and plates. Also test each cell with a hydrometer at least once each week. If the acid density in any cell is lower than that of the other cells, it generally indicates local action or a partial short circuit. A good overcharge at the 8-hour rate should be given the battery at least once each month. This overcharge should be continued until the cells have gassed freely about an hour.

The hydrometer used for measuring acid densities should be as large as possible to use conveniently, and with not too great a range; otherwise the scale will be too short and the divisions too close together to obtain accurate readings. In small hydrometers the error introduced by the meniscus that forms around the stem

REPORT ON BATTERY PLANT.

Number of Cells.............. Installed at...............

Type " "............... ....190...

No. Plates Per Cell...........

Glass Jars or Lead-Lined Tanks...................

Temperature of Battery Room....................°F.

" " Cells at End of Discharge...............°F.

" " " " " " Charge...............°F.

NO. OF CELL	VOLTAGE OF EACH CELL		SPECIFIC GRAVITY		Average Amp. Hrs. Discharged Per Day	Average Rate of Discharge	Color of Positive, whether Light or Dark Brown	Appearance of Negative	Note whether Positive Plates are Straight
	End of Charge at...Amp.	End of Discharge at...Amp.	At End of Charge	At End of Discharge					
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
61									
62									
63									
64									

FIG. 131. Record Blank.

at the surface of the liquid is considerable; in fact, so great that small density changes cannot be observed with any accuracy, if at all. Complete records of battery performance and condition of cells should be kept.

The blank form shown in Fig. 131 gives a good idea of the proper observations to make and method of tabulating.

Where the number of cells in a battery is large, frequent inspection of each cell is impracticable. In order to keep informed as to the general condition of the battery, without the necessity of testing each cell, pilot cells are tested and their conditions recorded as indicative of the condition of the group of cells of which it forms a part.

A pilot cell is simply one of a group, selected as a guide to the condition of the rest of the cells of the same group. Of course, an end cell cannot serve as a pilot cell, as a pilot cell must receive exactly the same usage as the cells for which it serves as an indicator.

The number of cells in a group for each pilot cell should not exceed 30. The pilot cell should have a hydrometer and a thermometer in it. A mark should be made on the inside of the tank at the normal level of the liquid surface, and the electrolyte should be brought exactly to this mark each day by the addition of distilled water only.

Daily readings from the pilot cell should be recorded on a blank form similar to that shown in Fig. 132. The hydrometer readings are plotted on the coördinate section of the blank,

The other battery cells should be individually inspected at least once each week. This is best accomplished by dividing the total number of cells into five or six groups and making observations of the cells in a single group, once each week, assigning a certain day for a certain group. The observations should be recorded on blank forms similar to that shown in Fig. 131.

Hydrometer readings of the pilot cell taken at any temperature other than the standard of 70 degrees F. should be corrected to 70 degrees by means of the curves, Plate I, or other convenient method.

In making connections, be sure that the proper polarities are joined together. Any voltmeter in which the controlling magnet is permanent will indicate the polarity, and its use will obviate errors. Keep all connections tight and clean; otherwise they will heat and corrode.

If batteries are used intermittently, and allowed to stand some time without charge or discharge, the electrolyte should be of low density, not over 1.210, and there should be not less than 15 lbs. of electrolyte per 100 ampere hours.

If avoidable, never allow a battery to stand uncharged any

DAILY RECORD OF PILOT CELL NO.________

Battery Owned By________________________________ Date________________

Number of Cells____________ Type____________________ Place____________________

Battery Room Temperature, Maximum__________ Minimum__________ Line Voltage, from________to________

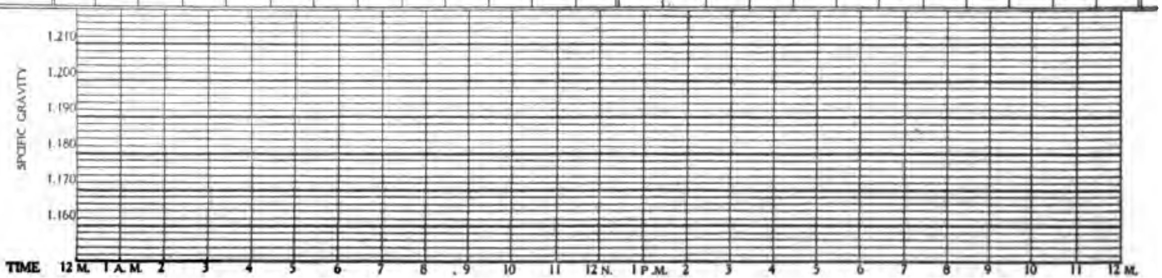
Battery Voltage, Maximum__________ Minimum__________ (To be obtained from Recording Meter) " ________ " ________

Wattmeter Reading, Charge__________ Discharge__________ " ________ " ________

Date of last Over-charge__________ Maximum Specific Gravity on last Over-charge__________

NOTE:—Record Gravity and Temperature Readings every hour, and Plot Specific Gravity in space ruled below for that purpose.

	MIDNIGHT											NOON												MIDNIGHT
Time	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Average Generator Load Amperes																									
Temperature																									
Specific Gravity																									



REMARKS:—(Note any trouble or unusual condition.)________________________________

____

____

Readings taken by________________ From________ To________

" " ________________ " ________ " ________

" " ________________ " ________ " ________

FIG. 132. Record Blank.

length of time, but charge immediately after discharge has taken place.

If plates become sulphated, it will be indicated by the positives first turning darker, and afterwards much lighter in color, and the negatives perhaps taking a slightly reddish hue. Also, the density of the acid will be lower in the sulphated cells than in the others. Locate the cause and remedy it at once, after which give the sulphated cells a good overcharge. When the density of the electrolyte becomes higher than normal, owing to evaporation, pure water must be added to bring the specific gravity to its proper value. This should be introduced into the cell at the bottom, by means of a short length of rubber hose or lead pipe extending down into the electrolyte. Water so put in will diffuse and mix itself with the acid, while if it were simply poured in at the top it would, by reason of its lower density, float, and would mix very slowly. Never change the density of the electrolyte except when the battery is fully charged. When water is put into cell, it should be before over-charge. The vigorous gassing which takes place at the end of the overcharge will thoroughly mix the electrolyte and the water.

If the batteries are to be put out of commission for some time — say six weeks or more — they should not be allowed to stand in the electrolyte unless a small charge be given them at least once in two weeks. Where they are to be unused for a considerable period, they should be fully charged. The electrolyte should then be drawn off, and immediately afterwards pure water put into the tanks. The cells should then be discharged through a resistance until the electro-motive force falls to about 0.5 volt. The water is then drawn off with a siphon or, if the cells are small, poured out, and the plates allowed to dry. Watch the negatives carefully, and if they begin to get very warm — say reach a temperature such that the hand cannot be held on them — sprinkle with a little water and bring down the temperature. Keep under observation until dry and no increase in temperature above a gentle warmth takes place.

While drying, do not let negatives touch each other, but keep well apart. It is a good rule not to let them be piled up on each other or come together even after drying, as the absorption of any moisture may cause them to heat to the point of destruction if all sides of the plates are not exposed and able to radiate heat.

When the batteries are again put into commission, it is only necessary to pour in electrolyte and give a complete developing charge.

Negative plates, when charged, should not be permitted to overheat when drying in atmosphere, as oxidization of the sponge-lead will take place very quickly, with the result that the plates may become so hot as to melt the grid and may fuse the active material.

Until negative plates are absolutely dry they must be kept well separated from each other.

Keep the outside of the containing cells as dry as possible and do not let them touch each other.

Never under any circumstances introduce any wire or metal into the cells.

If blisters or scale are to be removed, or an instrument has to be inserted in the cell for any purpose, use a flat strip or a rod of wood, glass or hard rubber.

Watch the accumulation of deposit in the bottom of the cell and be sure it is always well below the bottom of the plates. When it has piled up until it reaches near the electrodes, clean out the cell.

A convenient way to remove sediment from cells is to stir it up in the electrolyte and then siphon off the muddy liquid into a vessel where the sediment may again settle and the clear electrolyte be decanted and replaced in the cell.

When particles or plugs of active material become loosened, take a strip or rod, such as described above, and push the loosened material to the bottom of the cell. Otherwise it may drop between two adjacent plates and short-circuit the cell.

Whenever the plates are touched, do not rub hard against the active material, as that portion on the surface is soft and will come off and cloud the electrolyte so that inspection is made difficult. Be sure as to the purity of the water used for filling cells or mixing electrolyte. Water from natural sources seldom is free from injurious impurities, and the frequent addition of water to the cells will in time result in a concentration of impurities which will damage the elements. Never use water from hydrants or faucets, as it invariably contains iron in some form.

An approved type of still should be provided for the water supply. Rain water from perfectly clean wood, slate or tile roofs,

and filtered, may be used. The water should be stored in clean whisky or alcohol barrels, or in glass carboys well stoppered. Never use water from the condensation of exhaust steam containing cylinder oils.

Never strike a match or bring any flame near cells when they are being charged and are gassing. The released oxygen and hydrogen in air form an explosive mixture, and a disastrous explosion may result. Use only incandescent lamps to inspect cells. An electric spark will also explode the gases and therefore must also be avoided.

When wood or metal work becomes wet from acid spray, it will stay wet until the acid combines chemically with some substance or is wiped up with cloths or waste. It is good practice to wash off at intervals, the portions of the installation exposed to acid spray using a saturated solution of sodium bicarbonate (ordinary cooking soda). This will neutralize the acid. A subsequent washing with warm water should then be given the parts.

AUXILIARY APPARATUS, SYSTEMS, APPLICATIONS

PART II

CHAPTER XXIV.

USES OF BATTERIES.

STORAGE batteries find their principal uses in connection with power station and distribution work in (1) storage of electrical energy; (2) regulation of station output; (3) regulation of station voltage; (4) compensation for feeder drop; (5) insurance against shut downs; (6) as an equalizer on three-wire systems, and (7) a combination of any or all of the above.

(1) *Storage.*

As is well known, the load on any electric power station, whatever its character, differs from that on the power plant of a textile mill or other manufactory, in that it varies during the twenty-four hours from a minimum to a maximum. The fuel consumption and the cost of producing a horse-power hour are much less in a mill power plant than in an electric power station due to the fluctuating demand on the electrical plant. In designing an electric power station, provision must be made to supply the maximum load, which, however, usually lasts only a short time. Whether it is best to put in sufficient generating units and boilers to carry it and shut some of them down a large part of the twenty-four hours, or to install a battery to carry the peak, and if the latter, what proportion of the peak the battery shall take care of, depend on the conditions that obtain in the particular plant considered.

The battery will be charged when the load is light, and discharged when the demand is heavy, and thus partly equalize the load on the generating equipment with a resulting higher efficiency, in addition to giving the necessary output to supply the maximum demand on the system.

On the other hand, there are losses in the operation of the battery equipment which may partially or wholly offset these advantages. Whether a battery will pay dividends or not, and if so, the best ratio of battery capacity to capacity of generating equipment, depend on

a. Character of generating equipment.
b. Cost of fuel.
c. Cost of labor.
d. Character of service.
e. Load variations.
f. Cost of battery.

The cost of labor enters into the question only when the battery plant is to be so large that all or a large part of the boilers and generators may be shut down, at periods of light load, long enough to dispense with some or all of the attendants. This condition often exists in isolated plants having a very small night load.

The character of the generating equipment determines the fuel consumption for a given daily output which varies between wide limits, and its increase over the fuel consumed for an equivalent number of horse-power hours at steady load.

The cost of fuel per ton shows the value of the amount saved by steadying the load.

Character of service enters into the question apart from considerations of economy. With certain classes of service, a battery becomes a necessity, regardless of the financial considerations. A generator supplying current to both lights and elevators is a case in point. Without a battery, the winking of the lights when an elevator is started becomes intolerable. A battery will take up the load fluctuations and prevent this trouble. This, however, is an application belonging under the head of voltage regulation instead of power storage.

Load variations give the data from which the coal consumption is computed, as are also, the capacities of the battery and auxiliary apparatus.

Cost of battery equipment — which means the excess cost of a plant with a battery over an equivalent plant without one — shows the additional investment required, and the consequent increase in the interest and depreciation account. This quantity is often negative, *i.e.*, the cost of equipment with battery may be less than that of a plant to carry the same load with generating capacity sufficient for the maximum demand.

(2) *Regulation of Load.*

Used on regulation, the function of the battery is to steady fluctuating loads. The generator delivers a steady current, while the external load rapidly fluctuates above and below this gener-

ator output. The differences are absorbed or given out by the battery, that is, the battery receives a charge when the load is less than the normal generator output, and it discharges when the load is greater than the normal generator output, the rate of charge and discharge at any instant being equal to the difference between the generator current and that of the external circuit.

The economy of steam engines is worst on a rapidly fluctuating load, and the quick changes cause shocks and strains in the machinery which greatly increase the depreciation and repairs. A battery equipment on such a load produces a marked improvement in the fuel economy and the general operation of the plant, and reduces the cost of maintenance, besides, in many instances, allowing one or more machines to be shut down. As has been seen, the efficiency of a battery which alternates rapidly in its charge and discharge is very high, and these are the conditions under which regulating batteries work. Furthermore, the amount of energy stored in the batteries is very small compared with the total station output. The battery losses being proportionately small, the electrical efficiency is not appreciably lowered while the plant efficiency is greatly increased. Obviously, the battery may be used both to equalize the momentary fluctuations and to carry the peak when the steady demand increases. When gas engines are used as prime movers, and the generators driven by them supply a fluctuating load, a regulating battery is almost a necessity. Gas engines work best on a steady load, and on widely changing loads are liable to incomplete combustion in the cylinders with consequent soot deposits and trouble incident to this condition.

Also a gas engine has no overload capacity, and a demand even slightly in excess of the engine rating will cause it to slow down and finally stop.

A regulating battery will keep the load constant on a gas engine and allow it to run at its most efficient load, besides taking care of demands in excess of the capacity of the engine.

(3) *Voltage Regulation.*

The voltage regulation is obtained by regulating the station output. Certain classes of service demand voltage regulation though output regulation *per se* would not be required.

(4) *Compensation for feeder drop.*

When a battery is installed at the end of a long feeder, which supplies current to a rapidly and widely fluctuating load on which

the voltage drop must not exceed a certain amount, a saving of copper is effected, and in many cases this saving exceeds the cost of the battery.

Without the battery the feeders must be large enough to carry the *maximum* current at the prescribed voltage drop, while with the battery the feeders need only be large enough to carry the *average* current. The ratio of the average to the maximum demand determines the value of the application in this case. Here, too, the battery partially equalizes the instantaneous fluctuating load on the station and generating equipment, and it may also carry the peak on the feeder.

(5) *Safeguard against shut down.*

There are many cases in which a battery serves as a safeguard against breakdowns only, for instance, when connected across exciter bus bars in a large power station equipped with alternating-current generators. If an exciter should fail, the plant would have to shut down. A small battery kept charged would do no work and pay no dividends, but it would effectually prevent any such contingency, and the insurance effected would be well worth the cost.

As a rule, however, batteries are installed to equalize fluctuations, carry peaks and act as safeguards against breakdowns, all of which one battery is capable of accomplishing.

(6) *Acting as an equalizer on three-wire systems.*

When installed as an equalizer, the battery is connected across the outside wires, the neutral being connected to the cell in the middle of the series. Should unbalancing of the system occur, one-half the cells receive a charge, and the other half a discharge.

(7) There are many *combinations* of these important functions which a battery performs, the most of which will be illustrated later by concrete examples.

CHAPTER XXV.

PILOT CELL ACCESSORIES.

In order to take frequent records of the condition of the pilot cell and maintain it in a uniform condition certain accessory devices have been produced. The principal ones are, compensating hydrometer, signaling hydrometer, automatic cell-filling bottle, ampere-hour meter.

The compensating hydrometer is intended to give, directly, the density of the electrolyte referred to the standard temperature of 70 degrees without the necessity of temperature corrections.

Changes in the temperature of the electrolyte always produce variation in the specific gravity readings obtained by the ordinary hydrometer; for each 3° F. rise in temperature the specific gravity is lowered by one point (.001 sp. gr.) and is raised one point if the temperature drops 3°. Subject to ordinary weather conditions, a battery may normally change its temperature by as much as 20° within the course of a week, and occasionally by very much more than this; this would produce a change of 7 points in gravity, without any charge or discharge, which is equivalent to from twenty to forty per cent of the total working range.



Fig. 134. Compensating Hydrometer.

When the compensating hydrometer is properly adjusted, the small bent tube inside (see Fig. 134) is completely filled with electrolyte, about up to the small inner bulb, which latter is filled with air. The compensation is accomplished by the expansion or contraction of the air in the bulb, which forces out or draws into the tube a small amount of electrolyte, thus altering the weight of the instrument in conformity with such changes in gravity of the electrolyte in the cell as are due to variations of its temperature.

In adjusting the compensating hydrometer a standard battery hydrometer reading to one point, (.001 sp. gr.), and a battery thermometer are necessary.

After the battery has been charged, and before discharging, carefully read the specific gravity of the pilot cell with the standard hydrometer, and at the same time note the temperature of the electrolyte. Then correct the gravity reading to what it would be if the temperature were 70° F., by subtracting one point (.001 sp. gr.) for each 3° F. below 70° F. and adding one point (.001 sp. gr.) for each 3° F. above 70° F.; thus, if the standard hydrometer reads 1.207 at 79° F., its corrected reading is 1.210.

When the corrected reading has been obtained, insert the empty compensating hydrometer in the electrolyte of the pilot cell, then remove it and by inverting it allow the electrolyte in the small tube to run into the bulb, repeating this operation until the compensating hydrometer reads within two points (.002 sp. gr.) of the corrected reading of the standard hydrometer. If too much electrolyte has been introduced into the bulb, the excess can be removed by working in a sufficient number of bubbles of air; the size of the air bubbles admitted can be regulated by placing the finger partly over the opening. The excess of electrolyte must not be thrown out by heating the instrument.

On the day following the first adjustment, the instrument should be compared with the standard hydrometer, the reading of which should be corrected for temperature, as explained above, and the compensating hydrometer adjusted if necessary; then during the first month it should be compared weekly, after which it will require but infrequent adjustment. It is especially important, however, that the instrument be not allowed to read more than two points (.002 sp. gr.) higher than the corrected reading of the standard hydrometer.

In using this instrument, it must be borne in mind that it requires some time to adjust itself to the temperature of the electrolyte in which it floats; so if moved from one cell to another of a different temperature, at least fifteen minutes must elapse before a reading is taken. As long as it remains in one cell, it will follow any temperature changes that may there occur.

Signaling hydrometer.

The signaling hydrometer is based on the principle of the compensating hydrometer, and is used to give an alarm when the specific gravity of the electrolyte has reached a certain value.

The specific gravity of the electrolyte is the best indicator of

the state of charge of a storage battery; but it is often troublesome or impossible for an attendant to take a sufficient number of readings to determine accurately, when the gravity has reached a predetermined point, either on charge or discharge. The signaling hydrometer automatically corrects for temperature, and gives notice at the switchboard when the specific gravity reaches the desired point.

The fundamental principle of the instrument is that of measuring by means of a delicate balance the varying resultant weight of a bulb of constant volume totally submerged in the electrolyte. It is filled with electrolyte, and as change in temperature of the surrounding electrolyte causes expansion or contraction of that within the bulb, some of it is ejected or drawn in in such amount

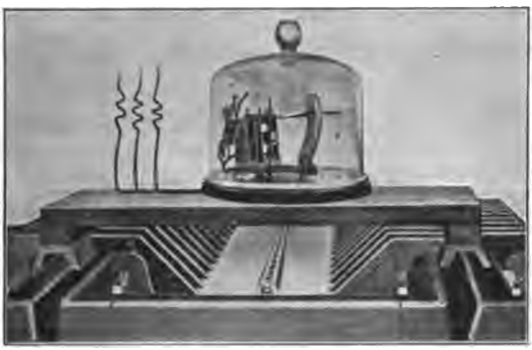


FIG. 135. Signaling Hydrometer.

as to cause the weight of the bulb to change inversely with the temperature, being in effect the same as the action of the compensating hydrometer previously described.

A balance arm indicates by a pointer and a scale what the specific gravity is at any time, and by means of two platinum contacts closes a circuit that notifies the operator when a given specific gravity has been reached, either on charge or discharge.

This instrument is shown in Fig. 135, mounted over a pilot cell. Fig. 136 shows the working parts.

Referring to Fig. 136, A indicates the balance spindle, carrying the arms B and C and the counter weights D and E. B is the main arm, carrying the pointer F and the hook G, on which hangs the platinum wire H, insulated at I, to which the glass bulb in the cell is attached. The counter weights D and E are for the adjustment of the

balance, while C carries a platinum plate W, for making contact with the platinum points S and T. The position of the arm J, carrying the pointer M and the contact screws Q and R, is controlled by the thumb nut L. The pointer M indicates the reading on scale N at

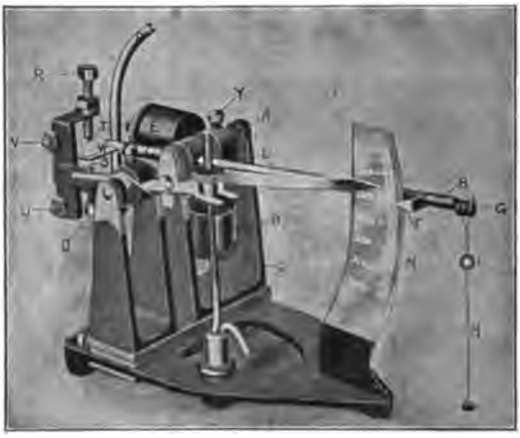


FIG. 136. Signaling Hydrometer in Detail.

which contact with S is made and the "charging" signal given. It is, of course, intended that M shall be set at any desired point. P is a guard for protecting the mechanism when putting on or removing the glass cover, and is fastened to the baseboard separately from the rest of the instrument.

Recording hydrometer.

A recording instrument which makes a continuous record of the electrolyte density is also made, based on these same principles, the mechanism being substantially the same as that shown in Fig. 136, with the addition of a drum rotated by clockwork, and a siphon pen, attached to the lever that is moved by the hydrometer bulb.

The *automatic cell-filling bottle* is used to maintain the level of the electrolyte constant in the pilot cell. One form of this device is shown in Fig. 137. It consists of a large bottle having an opening near the bottom, the mouth of the bottle being closed with a cork through which two tubes pass. From the bottom opening, a tube runs to the pilot cell and extends downward nearly to the bottom of the cell. A stopcock is put in this tube near the bottle as

shown. Of the two tubes which pass through the cork, one has a funnel at its upper end, a stopcock being placed below the funnel. The other tube connects with a vertical glass pipe which has its lower end fixed at a height coinciding with the level at which the electrolyte is to be maintained.

The bottle is filled with distilled water through the funnel, the stopcock in the upper tube being open and that in the lower tube being closed. When the bottle is filled, the valve in the funnel tube is closed and that in the lower tube is opened. If the electrolyte

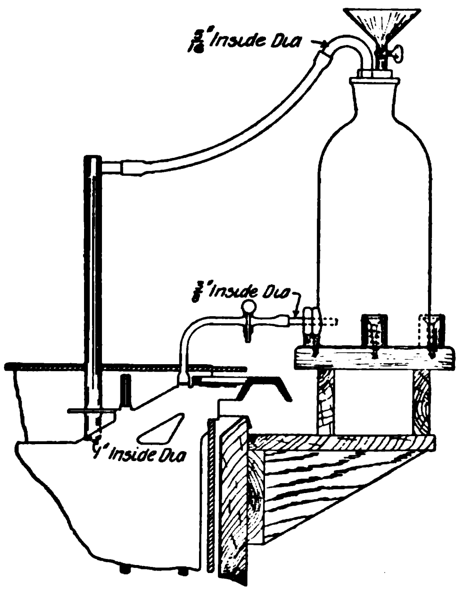


FIG. 137. Automatic Cell Filling Bottle.

is at a level lower than that of the end of the tube connecting with the opening through the cork, water will run out of the bottle, through the lower tube into the cell, and fill the latter. When the level of the electrolyte rises to the end of the tube leading to the cork, flow from the bottle ceases, because no air can enter the bottle to fill the space left vacant by the outgoing liquid. The electrolyte, therefore, seals the bottle when it covers the lower end of the tube leading to the opening in the cork.

The *ampere-hour meter* is an electro-dynamic instrument which has a needle or hand that rotates over a dial, and the hand points,

at any instant, to the number on the dial corresponding to the net ampere-hours output or input of the battery. The hand moves in either direction, turning clockwise for discharge and counter-clockwise for charge. When the hand points to zero, the cell has had the same number of ampere-hours put into it on charge, as have been given out on discharge. Obviously the position of the hand shows, at any time, the net charge or discharge the cell has received or given out.

CHAPTER XXVI.

END CELLS.

The voltage of a storage battery being variable, changing with the amount of charge it contains, and with the direction of current flow, devices are required to compensate for this variation and maintain a constant potential on the line which is supplied by the battery.

The methods which are in use are the following:

(1) End cells.
(2) Variable resistances.
(3) Counter electro-motive force cells.
(4) Boosters.
(5) Combinations of the above.

End cells are the cells at one end of a group which have individual connections with the contacts of a special form of switch, by

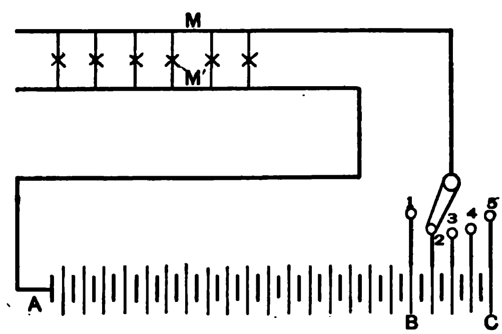


Fig. 138. Battery with End Cells.

means of which these end cells may be put into or taken out of the circuit, in series with the other cells of the group.

Referring to Fig. 138, MM' are supply mains, AC the battery, 1, 2, 3, 4, and 5 switch contacts, each of which is connected with an end cell; a movable contact arm being connected to the main M.

When the battery is fully charged, the voltage per cell on beginning of discharge will be about 2.05, and if MM′ be a 110-volt circuit, the number of cells required in series would be $\frac{110}{2.05} = 53$.

When the battery is near exhaustion, however, the voltage per cell on discharge is 1.8, and the number of cells required in series $= \frac{110}{1.8} = 61$. Therefore it is necessary to gradually vary the number of cells in circuit from 53 to 61, between the beginning and end of discharge. The installation would consist of 61 cells, eight of which would be end cells, with taps running to contacts on the end cell switch. These switches are considered in detail in Chapter XXVIII.

The taps must be of sufficient cross-sectional area to carry the maximum current discharged, as each becomes one side of the system when the contact arm of the end cell switch rests on the switch contact to which the tap is connected.

Since the end cells are gradually cut out as discharge proceeds, it is evident that they need not be of the same capacity as the cells forming the main body of the battery. Theoretically, they should taper off in size, the extreme outer cell being the smallest, and the cell adjacent to the main battery of the same capacity as the main cells. In practice, however, it is customary to install all the cells of uniform size, and in case of loss of capacity or accident to any of the main cells, one of the end cells may be substituted for it, the defective cell taking the place of the removed end cell, and furnishing sufficient capacity to make the system operative.

In charging, the extreme end cell — the one first cut out of circuit on discharge — will soon be fully charged, as but little current is taken out of it. The end cell switch must then be moved on to the next point, cutting out this charged cell. When the next cell is fully charged, it is also cut out by moving in the end cell switch, and so on until all the end cells have been cut out. All the cells in the main battery will, of course, be charged for the same length of time. Care must be taken to cut the end cells out as they become fully charged, or they will be overcharged, and possibly to such an extent as will injure them.

Fig. 139 shows a type of installation in which the end cells must be larger than those in the main battery. G is the supply generator in which the voltage may be varied above that of the supply

circuit MM′. AB is the main battery, and BC the end cells. S_1 and S_2 are end cell switches.

The maximum voltage of the generator must be great enough to charge all the cells in series, and as the battery fills up, the movable arm of S_1 is carried along towards B, cutting out the end cells.

The arm of S_2 is placed on the contact which puts in series the exact number of cells required to give the proper voltage across the supply mains MM′.

It is evident that the current flowing through AB is the charging

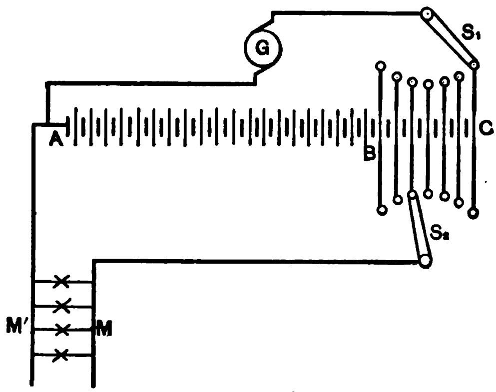


FIG. 139. Battery with Double End Cell Switch.

current, while the current through the end cells included between the arms of S_1 and S_2 is that through AB, plus the current used in the supply mains. The end cells in this system must, therefore, be large enough to admit of the passage of the total current used in the system.

The number of end cells will be the same in any case — about 13½ per cent of the total number of cells in the battery.

CHAPTER XXVII.

CONTROL BY COUNTER CELLS AND RESISTANCES.

INSTEAD of end cells, counter electro-motive force cells or resistances may be used to maintain the line voltage constant. Counter electro-motive force cells are made of grids or other lead plates immersed in ordinary electrolyte. The plates are not formed or covered with active material, and possess no capacity. Their sole function is to set up a voltage opposing that of the discharge current, and cut down the net voltage across the line by an amount depending on the number of counter cells in series which oppose the pressure of the main battery. As the voltage of the main battery falls, the counter cells are cut out, and the external voltage of the system is in this way kept constant.

The same number of useful cells are required as would be if some were tapped off as end cells, viz.: $\frac{E}{1.8}$, in which E = voltage of the system.

The same number of counter cells are required as would be of end cells if the latter were used, that is, about 13½ per cent of the number of cells in the battery. The counter cells require the same connections to a multiple-point switch as do end cells. It is seen, therefore, that the use of counter cells does not reduce the number of cells, but adds 13½ per cent of cells of a different type from the useful cells, thus complicating the installation and increasing its cost by an amount equal to the value of the counter cells. For these reasons they are now seldom installed, and except in cases of plants which receive little or no attention when being charged, should never be used. The one valuable feature of an installation of this kind lies in the fact that all the cells of the battery are uniformly charged and discharged, while with end cells these latter are never worked to their capacity, and are subject to severe overcharge, unless some attention is given the plant during the period of charging, and the contact switch shifted as the cells are filled up.

As a matter of fact, in practice, the end cells are nearly always in

better condition than those in the main body of the battery, and the attention necessary to prevent injurious overcharge is very slight, so that, except in very rare instances, the counter cell may be considered as having no place in the storage battery practice of the present time.

Resistances are often used for voltage regulation in small installations where efficiency is not so important as simplicity and low first cost, such as small country house lighting plants, yacht installations, and the like.

In nearly every instance they are used for the double purpose of regulating the current flow on charge as well as the voltage on discharge. In small plants the battery is divided into sections which may be switched in parallel, and the voltage required to charge the parallel groups is lower than that of the generator, which has a potential equal to that of the supply mains.

Thus if a 110-volt system has a 110-volt generator and also a battery which is to work in parallel with the generator, the number of battery cells will be $\frac{110}{1.8} = 61$. To charge these cells all in series will require $61 \times 2.5 = 153$ volts, which the generator cannot supply. If 62 cells be installed and these divided into two parallel groups of 31 cells each, the voltage required to charge will be $31 \times 2.5 = 77.5$ volts. This, however, is much below the generator potential, and therefore, to prevent excessive current flow, a resistance must be inserted between the generator and each group of cells, and this resistance must be variable in order to compensate for the change in battery potential at different stages of charge. After full charge, the two groups of cells are connected in series, and their potential at the beginning of discharge is $2.05 \times 61 = 125$ volts. Discharge must therefore take place through the variable resistance which causes the drop necessary to reduce the battery potential to that of the generator. As the battery voltage falls on discharge, the resistance is reduced, all the resistance being out of circuit when the potential of the battery has fallen to 110 volts. Fig. 140 shows the connections of an installation of this character.

The use of resistances has the advantage of producing a compact, low cost, and simple plant which requires no auxiliary charging dynamo or "booster," and can be charged by the generator while it also supplies the external load at a constant voltage. Obviously,

however, it is very inefficient, a large portion of the energy, both of charge and discharge, being lost in the resistance.

The usual resistances are made of iron or german silver wire, though for heavy currents cast-iron grids are used. They have a number of taps connected to contact points of proper area, over which a movable arm travels and makes contact with the tap points. In designing these resistances, the maximum current flow will fix the cross section of the resistance material while the maximum

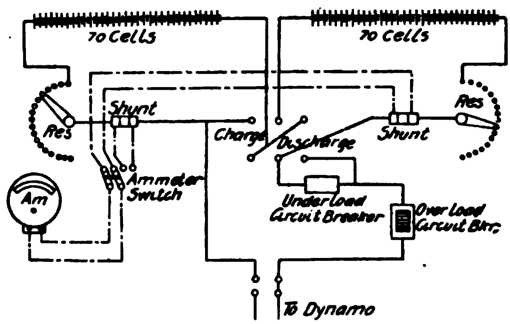


FIG. 140. Battery for Multiple Grouping with Controlling Resistances.

voltage drop necessary with minimum current will determine the amount of the resistance.

These data are obtainable from the load curve or may be taken from the size of the battery. The best practice is to design the resistances to carry the maximum current that the battery can discharge, and to neglect the load curve, which latter may change at any time, and require a rate of discharge that would be injurious to the resistances.

CHAPTER XXVIII.

END CELL SWITCHES.

WHEN end cells or counter cells are used for regulation, a special form of switch, termed "end cell switch," must be installed. The purpose of this device is to cut cells in or out, as may be necessary to maintain a constant voltage across the line. These switches commonly consist of a number of contacts equal to one more than the number of end cells, and a moving contact arm. Each end cell is connected to a contact piece, the connections being made in regular order, so that adjacent contact pieces are connected to end cells that are also adjacent. Fig. 141 shows diagrammatically, how the connections are made, and it is obvious that as the moving

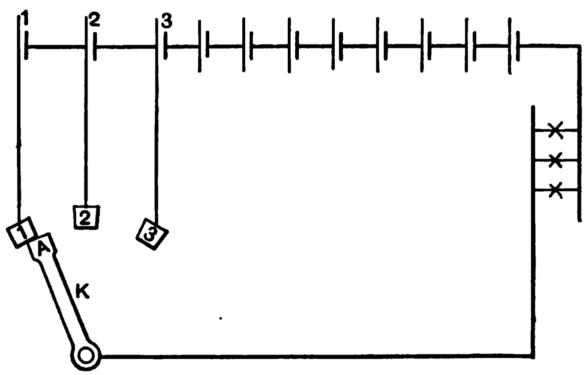


FIG. 141. End Cell Switch.

contact arm travels to the left, more cells are gradually put into the series circuit.

The end cell switch is more complicated than an ordinary contact switch, because it is necessary to avoid either opening the circuit in moving from one point to the next, or short-circuiting any of the cells. Referring to Fig. 141, it is seen that if the end A of the moving arm K leaves the contact 1 before it touches contact 2, the lighting circuit will be opened. If it touches 2 before it leaves 1, cell No. 1 will be short-circuited.

There are three methods by which this short-circuiting is avoided when the two adjacent contacts are connected by the moving contact arm. They are as follows:

(1) Double contact on arm joined by resistance.
(2) Double contact on each end cell connection joined by resistance.
(3) Counter electro-motive force cell which is interposed in the circuit.

The first of these is the most universally used, and adequately meets all requirements. Fig. 142 shows the principle of its operation. 1, 2 and 3 are contacts joined to corresponding end cells. A is the main contact on the moving arm. B is an auxiliary contact fastened to A by the insulating piece C, and R is a resistance connecting A and B. The arm is shown in the act of passing from contact 1 to contact 2. A has not left 1; B is on 2 and therefore the

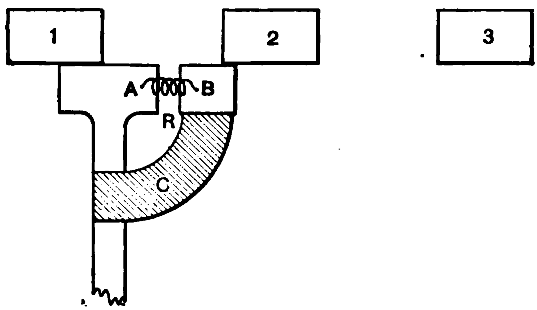
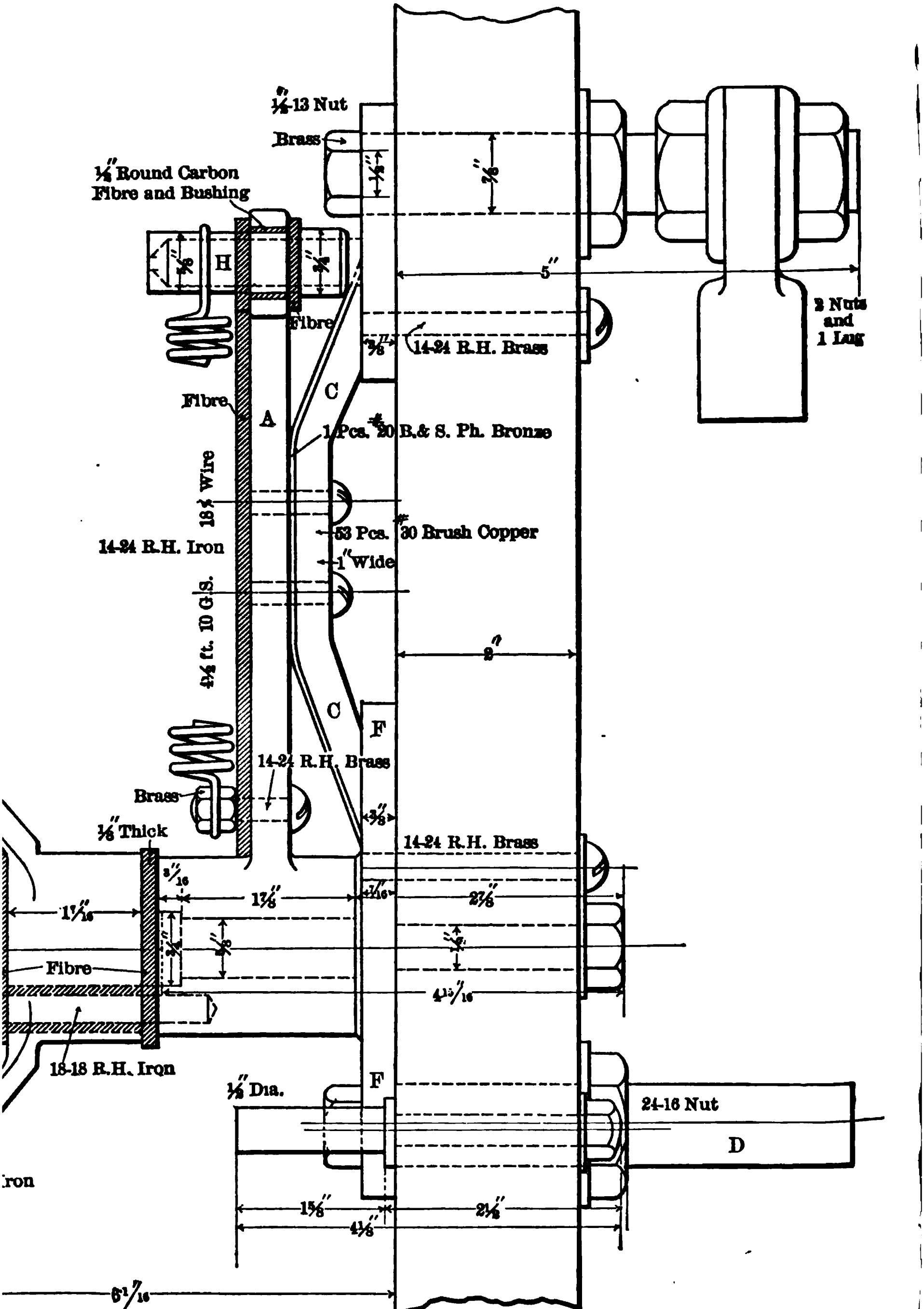


FIG. 142. End Cell Switch, Detail.

circuit is not broken. The current from 2 to the outside circuit passes through R, which is of such low resistance that it causes no perceptible drop in the outside circuit, yet it is great enough to prevent the cell from being short-circuited and discharging an excessive amount of current, for, although the resistance is low, the short-circuiting voltage is also low, being simply the 2 volts of the single cell.

The arrangement of a double contact on each connection with a resistance between the two contacts is shown in one of its forms in Fig. 143. a, a, a, a are the main leads to their respective contacts; b, b, b, b are auxiliary connectors to the auxiliary contacts. These connectors are made of some resistance metal — generally iron — that opposes the flow of current sufficiently to prevent a



1/2-13 Nut
Brass
1/4" Round Carbon Fibre and Bushing
H
Fibre
5"
3 Nuts and 1 Lug
14-24 R.H. Brass
Fibre
A
C
1 Pcs. #20 B.& S. Ph. Bronze
18 ½ Wire
53 Pcs. #30 Brush Copper
14-24 R.H. Iron
1" Wide
4½ ft. 10 G.S.
2"
C
F
14-24 R.H. Brass
Brass
1/8" Thick
14-24 R.H. Brass
1 7/8"
2 7/8"
1 1/16"
Fibre
4 15/16"
18-18 R.H. Iron
F
1/2" Dia.
24-16 Nut
D
Iron
1 5/8"
2 1/8"
4 1/8"
6 17/16

short circuit. It is immaterial, of course, where the resistance is placed, or how connected, if it is interposed in the circuit at the time two adjacent contacts are connected together.

The smaller sizes of end cell switches are made circular, that is, the contacts are laid out around a central pivot or axle about which latter the moving contact arm turns. Plate III shows an elevation and cross section of a standard switch of this kind for 11 end cells, and with a carrying capacity of 300 amperes normal.

The edges of the contact pieces are radial, and the distance of separation is one and one-eighth inches. The terminals of the contacts are shown on the back of the panel.

The gaps between the contact strips are filled flush with flat thin pieces of fiber, making the surface from contact to contact smooth and even.

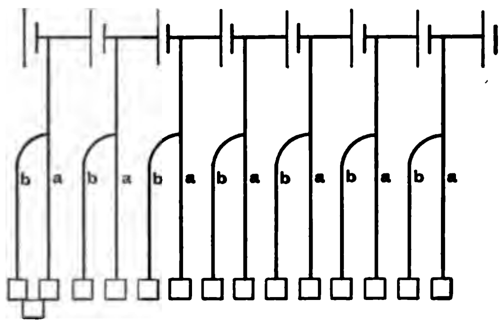


Fig. 143. End Cell Switch, Detail.

The moving contact arm A carries on its under side a double-ended, laminated contact piece C, the outer end of which rests on the smooth circular track of fiber and contacts, traveling on it as the hand wheel E is turned. This end, therefore, can be placed over any contact piece.

The inner end of the moving contact piece rests on a solid circular plate of copper F, which is provided with the terminal D.

Since the moving contact connects the ring F with any of the contacts spaced around the circle, any end cell may be connected with the terminal D, as required.

The auxiliary contact, by means of which the breaking of the circuit in passing from one contact to another is avoided, is shown at H, and consists of a five-eighths-inch, round carbon passing through a hole in arm A. This hole is drilled in an offset on the

arm, as shown, and therefore is in advance of, or behind the main contact piece C, according as the motion is clockwise or the reverse. The hole is bushed with fiber (see section), and the carbon contact is therefore insulated from the arm and the moving contact. A resistance coil of German silver connects the carbon to the arm, and consequently, to the main moving contact.

It may be noted here that the proper current densities for contacts are 60 to 70 amperes per square inch with ordinary contacts, and 300 to 400 amperes per square inch in laminated, leaf contacts. The latter are used almost exclusively on switches of 300 amperes capacity and above.

End cell switches in the larger sizes are made straight, the movable contact moving along a screw or rack. Fig. 144 shows one of this kind, made by the Electric Storage Battery Company.

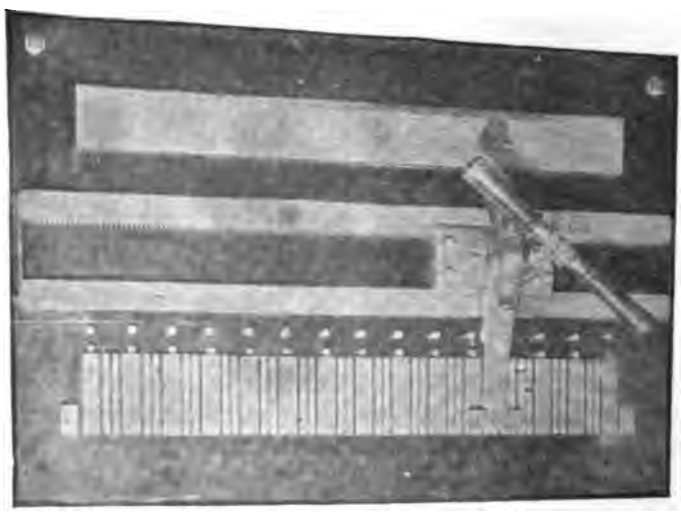


Fig. 144. Horizontal End Cell Switch.

The type of end cell switch in which a counter cell is used instead of a resistance is shown diagrammatically in Fig. 145.

As is seen, there are two sets of contacts, two contact bars A and B, and two moving contact arms L and M. The end cell connections are joined directly to C_1, C_2, C_3 and C_1', C_2', C_3'. The contacts are so spaced that C_2, C_3, C_4 are below or opposite to spaces between C_1', C_2', C_3'. The moving arms L and M travel along together, but are insulated from each other, as are the

bars A and B. T is the terminal of the end cell side of the system.

In the position shown, C_2 is connected through M to A and thence to T; L, being on a space, is open-circuited. As L and M travel toward the right, L moves on to C_3' and joins it to B before M moves off of C_2, and the circuit to T is made through E, which sets up a counter electro-motive force of over two volts and although the two adjacent cells are joined to T at this instant, short circuit is prevented by the counter electro-motive force of E.

Further movement brings L fully over C_3 and M over a space, the current all passing through E, and though one end cell has been added to the circuit, no rise in voltage has occurred because the

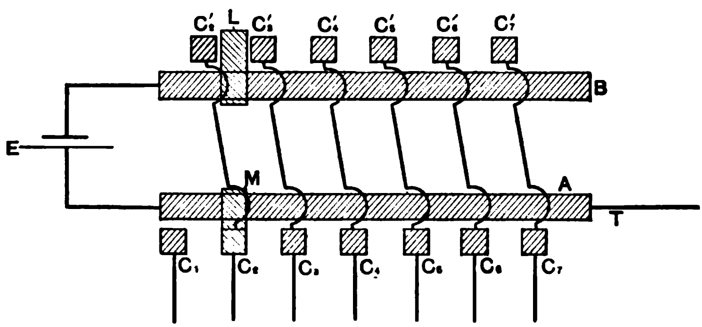


FIG. 145. Counter E.M.F. End Cell Switch.

counter potential of E neutralizes the voltage of the added cell. As L and M continue their motion M reaches C_3 and at that moment the voltage of the system is raised. When M is in its final position over C_3, L is on a space.

It is obvious that a resistance between A and B in place of the cell E would serve to prevent a short circuit across the end cells.

This switch can be modified in many ways, the principle being retained; for instance, C_1, C_2, C_3 may be directly below or opposite to C_1', C_2', C_3', and one contact arm set in advance of the other an amount equal to one-half the pitch of the end cell contacts.

When laminated contact brushes are used, the thin ends of the individual laminae will wear into the surface of the contact segments, and produce numerous small grooves, unless some provision is made to prevent this scoring.

Two methods of accomplishing this are in general use, and in

both the scoring is prevented by mounting or twisting the laminations so that the ends, in contact with the contact segments, are not parallel to the direction of motion of the brush, but make a small angle with it. As the brush is moved along its path the end of each lamination moves over a surface much wider than the thickness of the lamination, and the surface traveled over by each lamination overlaps similar surfaces traversed by adjacent laminations.

In the Bijur switch, later described, the brush is set slightly diagonal with respect to the axis of the switch, while in the Appleton switch the brush is set at right angles to the axis of the switch, but the ends of the laminations are bent to a position which is diagonal to the path of motion of the brush. Fig. 146

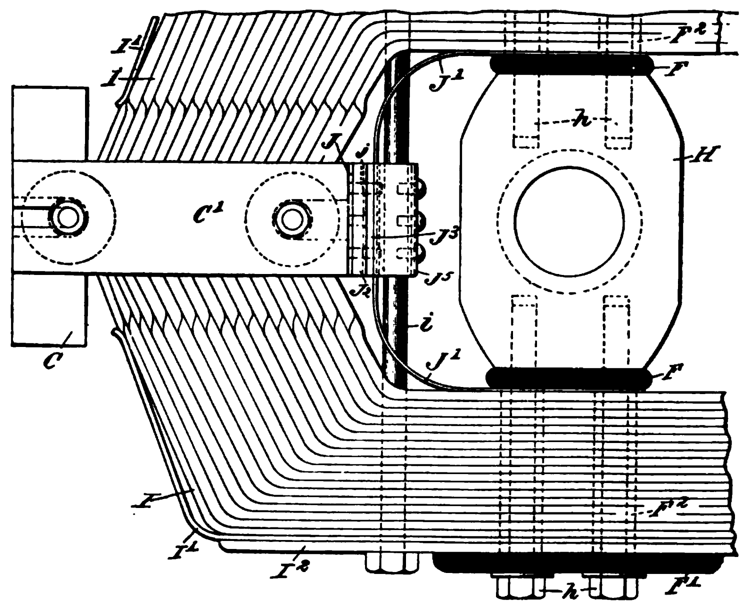


Fig. 146. Detail of Switch Brush with Twisted Ends.

shows the form of the brush on the Appleton switch made by the Electric Storage Battery Company.

The switches before described are moved from one contact to the next by hand, and require the attention of the station attendant.

Motor-driven switches have been devised which are actuated by closing a switch or contact at the switchboard and which are now in successful use.

In America, they are controlled by a small hand switch or push button which is moved by the attendant. In Europe, however, there is a number of installations in which the controlling switch is closed by a relay, the latter being actuated by some form of contact voltmeter — such as a spring-controlled solenoid. These are, of course, completely automatic. They are, however, somewhat complicated, and in case the contact maker or relay should

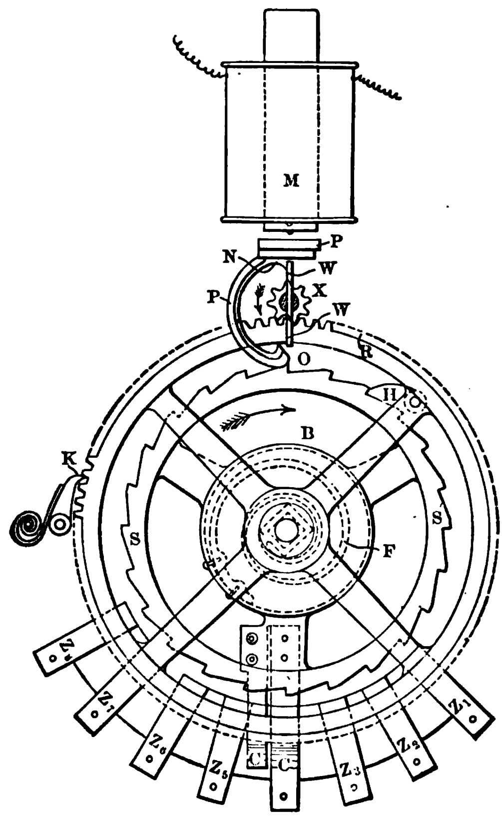


FIG. 147. Escapement End Cell Switch.

stick or fail to move, the result might be harmful to the battery. For these reasons they have never come into use in America, the semi-automatic or hand-switch-controlled type being almost universally used.

The fact that the moving contact arm must travel a definite distance each time it is moved, makes the design of an automatic

end cell switch much more complicated than would at first appear. If the switch be set in motion, and the current actuating the driving motor be stopped too soon, or allowed to flow too long, the result will be a lapping or bridging of contacts. For this reason every

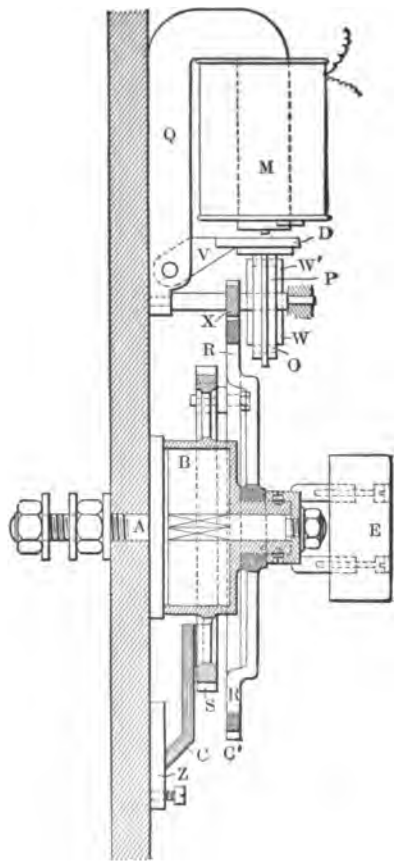


FIG. 148. Escapement End Cell Switch, Sectional Side View.

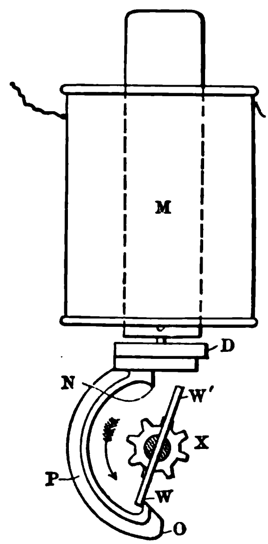


FIG. 149. Escapement End Cell Switch, Detail of Magnet and Escapement.

automatic end cell switch must be so designed that, though it is initially set in motion by some form of switch or contact, after starting it will move a definite distance equal to the pitch of the cell contacts, regardless of the opening of the actuating switch.

Escapement switch.

The simplest of the automatic switches is shown in Figs. 147,

148 and 149. Fig. 147 is a front view, Fig. 148 a vertical section, and Fig 149 a separate view of the solenoid escapement which controls the action of the switch. In the Figs. Z_1, Z_2, Z_3, etc., are contacts, C and C′, the moving contact arms, joined by a resistance, which latter is not shown. K is a pawl held into the teeth of wheel R by means of a spring, and which permits R to turn in one direction only. This wheel also meshes with a pinion X, which latter is unable to rotate unless the escapement N, P, O is moved up or down. The flat bar W, W′ is fastened to the pinion shaft and catches at one end or the other against one or the other of the escapement stops N, O when this shaft rotates through a half circumference.

A ratchet wheel, S, the central portion of which is formed into a flat circular box B, is mounted on the same shaft as R, but in a different vertical plane (see Fig. 148). Inside this box is wound a heavy spiral spring, F, like a clock or motor spring, one end of which is fastened to the circular box and the other to the squared shank of the axle A, around which both wheels turn. Obviously, if the wheel, S, be turned several revolutions in a counter-clockwise direction by means of the hand wheel E, which is fastened to S, the spring will be wound up and tend to turn S in the direction indicated by the arrow. Pawl H, which is fastened to R, catches in the ratchets of S, and any motion of S in a clockwise direction is transmitted to R, moving it and the contacts C, C′, which are joined to R.

The controlling magnet M has a closed iron path QV, which completes the magnetic circuit except the air gap between D and M. A joint allows V and D to vibrate.

When the magnet is excited by passage of current through its winding, D is lifted up and with it the escapement P. This allows the end W of the bar or wing to pass escapement catch N and the wheels S and R are rotated by the spring F, until the escapement catch O stops the motion of the pinion and, therefore, of the wheels (Fig. 149). The circuit to the magnet winding is now opened, and the escapement yoke falls to the position shown in Fig. 147, the half revolution of the pinion having been completed and the wheel R having moved just far enough to pass from one contact, Z, to the next.

The movement is controlled by a push button, which closes and opens the circuit through the magnet winding. It may be made

automatic by controlling the circuit through M with a contact voltmeter.

*The Appleton end cell switch** is shown diagrammatically in Fig. 150. M is the armature of the motor, which is geared to the screw shaft of the end cell switch; *f* the motor field, S_1 and S_2 special forms of switches, T a push button which when pressed pushes down the rod *i*, and the pieces N and X mounted thereon. *p*, *p'* and *h*, *h'* are pairs of contacts connected together by N and X

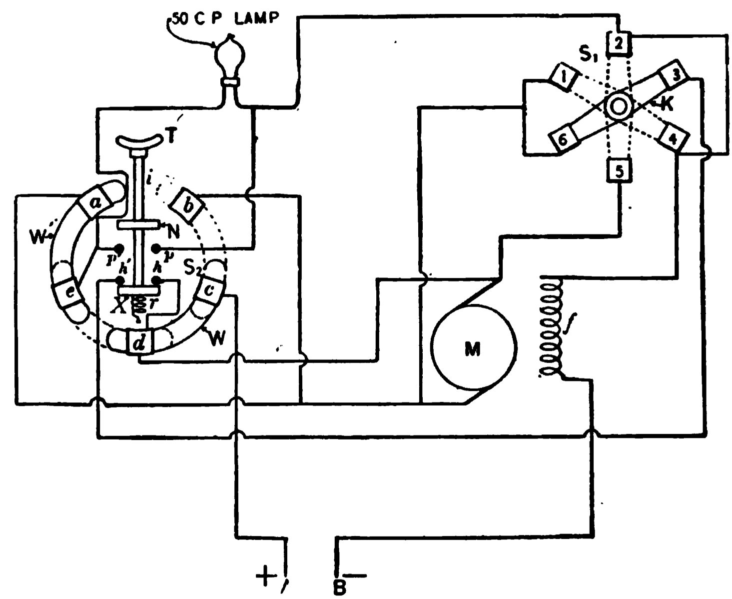


FIG. 150. Appleton End Cell Switch, Diagram of Connections.

respectively when these pieces touch the contacts; *r* is a spring which tends to push the rod and push button outwards, and normally holds X against *h* and *h'*.

S_2 consists of five contact points, *a*, *b*, *c*, *d*, and *e*, spaced about a circle. W and W' are contact arms bent to the arc of a circle. These are attached to a hand wheel and may be turned to connect different contacts together. In the position indicated by the full lines, *a* and *e* are connected together, as are also *c* and *d*. By turning the hand wheel, which is not shown (being omitted to avoid complicating the diagram), the contact arms W, W' may be

* Amer. Pat. 734291, July 21, 1903.

made to take the position shown by the dotted lines connecting *d* to *e* and *b* to *c*. The push-button rod *i* usually passes through the center of the hand wheel, the push button projecting above the latter.

S_1 consists of six contacts, 1, 2, 3, 4, 5, and 6, spaced about a circle. These contacts form three pairs, and any pair may be connected by the rotating arm K, which turns about a central pivot as shown. Normally, it is in the position shown by the full lines joining 3 and 6. As soon as the motor begins rotation, it changes to one of the positions shown by the dotted lines, this movement being automatically effected in a manner to be described.

A and B are the incoming mains from which current is taken to operate the switch.

M and S_1 are at the end cell switch, while T and S_2 are on the switchboard. With the connecting arms of S_2 in the position shown by the full lines, the motor can be started in a clockwise direction by pressing the push button T. Current flows continuously in the motor field *f*, the path being from A to *c*, to *d*, to *h*, to *h'*, to 3, to 6, to *a*, to *e*, through the lamp (which keeps down the field current) to 2, to 4, to *f*, to B. On pressing T, the circuit across *h* and *h'* is opened, and *p* and *p'* connected together. The path of the circuit now is A to *c*, to *d*, to M, to *a*, to *e*, to *p'*, to *p*, to 2, to 4, to *f*, to B. That is, the current is passing through the motor armature and field in series, the resistance lamp being cut out. A strong field is produced and the motor starts. Immediately K rotates and joins 1 and 4. If the push button still be held down, the path of the circuit is as before, and also a parallel path from A to *c*, to *d*, to M, to 1, to 4, to *f*, to B. If the button be released, spring *r* returns it to its normal position, and the main path of the current through points last given is unchanged, only the auxiliary path through the push-button contacts being opened. The motor, therefore, will continue to run after starting whether the button be held in position or released.

When the switch brush has moved such a distance as to register with the next succeeding contact segment, the arm K swings to its normal position, joining 3 and 6, and if the push button be released before this point is reached, the connections are then such that a current flows through the motor field — passing through the lamp — and the motor armature is short-circuited by the path M, 2, 3, *h'*, *h*, *d*, M. This short-circuiting in a magnetic

field causes an instantaneous braking effect and stops the motor and switch at the proper point of shoe travel.

If the switch is to move in a reverse direction the motor must also rotate in a reverse direction. The hand wheel of S_2 is turned so that W′ connects *e* and *d*, and W connects *b* and *c*. On pressing the button the motor will turn in a direction opposite to that in which it first rotated. On starting, K turns and joins 2 to 5, and the connections are in effect the same as before, except that the polarity of the armature connections are reversed, as may be seen by tracing them out.

The mechanism which actuates K is shown in Fig. 151. 10 is a shaft geared to the screw shaft of the end cell switch, and 9 is a

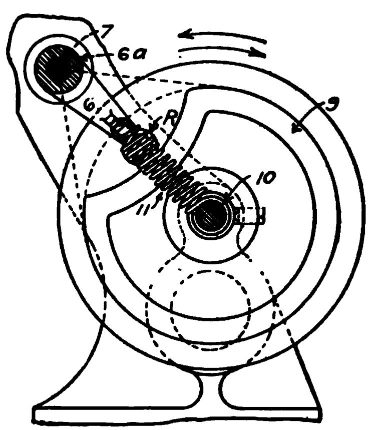


FIG. 151. Appleton End Cell Switch, Detail of Sustaining Switch.

flat cam mounted thereon. 6 is a switch lever which is fulcrumed on shaft 7, as shown. 11 is a spring which tends to hold 6 in its normal position, which is as indicated. R is a small roller at one end of 6, which runs into the recess in the cam when a revolution is completed. On shaft 7 the arm of switch K is mounted.

The cam shaft 10 is so geared to the screw shaft that when the contact shoe moves a distance equal to that from one contact to the next one adjacent, the cam makes one revolution.

On starting the motor, the upper end of arm 6 is thrown upwards or downwards by the cam, according to the direction of motor rotation, rotating shaft 7 through a small angle, which correspondingly turns K. When the revolution is completed, R is

returned to its position by spring 11, K is thrown to its normal position, short-circuiting the motor armature, and the rotation is instantly stopped.

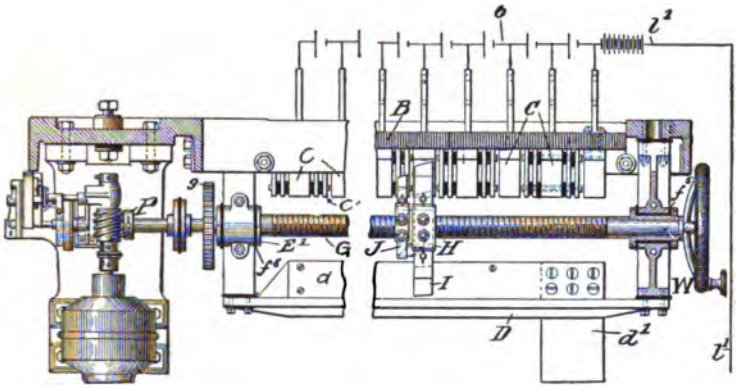


FIG. 152. Appleton End Cell Switch, Plan.

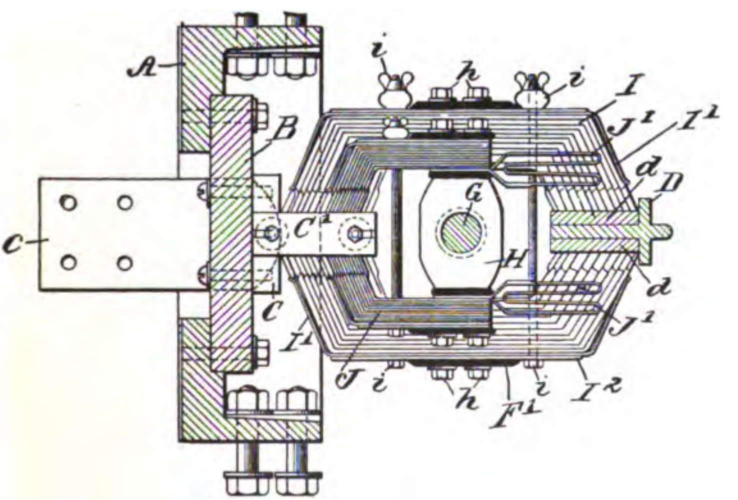


FIG. 153. Appleton End Cell Switch, Cross-Section.

The complete switch is shown in Fig 152, which is a plan view. At the extreme left are seen the cam and switch arm that move the sustaining switch.

The contact points are designated by C, and these are spaced apart by small bridging pieces of metal C′. These bridging pieces are bolted to the sides of the contacts, each alternate contact

carrying the bridging pieces on either side of it, while the other contacts have none fastened to them. The bridging pieces are insulated from the bolts passing through them and from the contact points.

A sectional view is shown in Fig. 153. In order to secure large current-carrying capacity, the nut on the screw shaft carries a pair of brushes, one above and one below. The broad flat ends of C

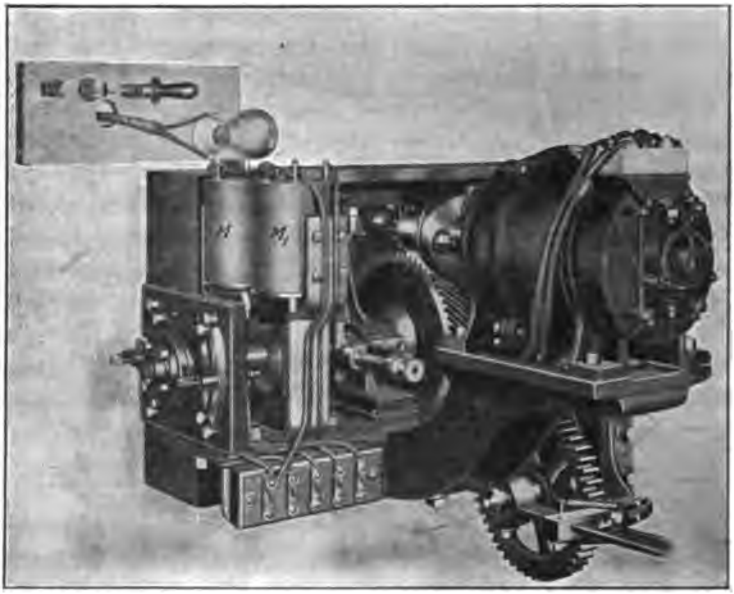


FIG. 154. Achard End Cell Switch, Motor and Controlling Mechanism.

are to give good contact surface with the ends of the copper bars from the end cells, which are bolted to these terminal ends.

The flat bars *d*, *d* on the side opposite to the contacts, are the switch bus bars to which the laminated brushes deliver current. The pressure of brushes against contacts or bus bars is adjusted by the wing nuts *i*, *i*, which screw on the ends of bolts passing through the main brushes I and I. The small brushes J are the advance brushes, J_1 being the resistances which connect the advance with the main brushes.

*The Achard Switch.**

This switch is somewhat similar to the Appleton switch, but is

* Amer. Pat. No. 955448, April 19, 1910.

improved by the application of larger motors with higher speed of gearing, magnetic motor-controlling devices and the reduction of the number of connecting wires to five instead of seven. Fig. 154 is a picture of the driving motor with gearing and control magnets. The manual control switch and signal lamp appear mounted on the small panel in the upper left-hand corner. The pairs of bosses set radially to the shaft and showing at the extreme left end of the picture are the contact points of the magnetically operated

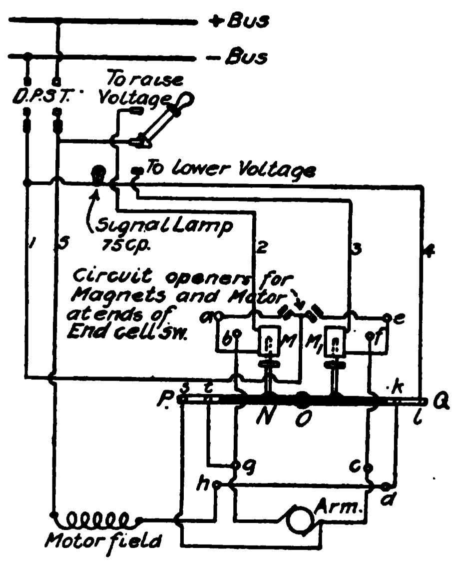


FIG. 155. Achard End Cell Switch, Diagram of Connections.

switch, later to be described. Fig. 155 is a diagram of the connections for this switch.

When the switch is at rest, the magnetic switch, represented by the horizontal bar N carrying the conducting ends P and Q and turning about pivot O, is in the position shown. There are six pairs of contact points, of which three pairs are arranged to be connected by the end P and three pairs to be connected by the end Q. When the contacts are in the position shown, the circuits are as follows: From positive wire 5 through motor field to contact *h*, thence to contact *d* and to contact *k*. From *k* through end Q of the magnetic switch to contact *l* and thence via wire 4 through the

signal lamp to negative wire 1, is one circuit. Current, therefore, always flows through the field, the lamp acting both as a resistance to reduce the current flow and as a visual signal.

A second closed circuit is that which short-circuits the motor armature brushes, through contacts *s*, *t*, which, in the inoperative position, are joined together by the end P of the magnetic switch.

If the switch is to be moved so that cells are added to the circuit, the hand switch is thrown to the upper contact and the following circuits result: From positive wire 5 through wire 2, through magnet M, thence through circuit openers (which are closed except when extreme travel of switch is reached) to negative wire 1. The magnet M being energized, moves the switch bar around pivot O, the end P contacting with contacts *a* and *b* while the end Q contacts with points *c* and *d*. Then from wire 5 through the field to point *d*, thence by end of lever Q to point *c* through the armature, thence to point *b*, now connected to *a*; from *a* through circuit openers to wire 1 the current travels, and the motor turns to drive the switch screw. When the rotation has proceeded far enough to move the switch brush from one contact to the adjacent one, a cam motion returns the magnetic control switch to its horizontal position. The connections, as before described, are then such that the field is energized, but the motor armature short-circuited. Motion of the motor is therefore immediately arrested and the movement of the main switch ceases, the brush registering with the switch contact.

By following out the connections in the same manner, it will be seen that, when the hand-control switch is thrown on the lower contact, magnet M_1 is energized, the bar N moves about pivot O so that the end Q joins contacts *f* and *e* while the end P connects contacts *h* and *g*. Current will flow through the field in the same direction as before, but its direction through the armature will be reversed. Consequently the direction of rotation of the motor will be reversed and the switch screw will be rotated to move the brush in a direction to cut out end cells, until it passes from the contact, on which it was at rest, to the next adjacent one. The cam on the switch shaft then acts to throw the magnetic-control switch back to its neutral position, short-circuiting the motor armature and causing immediate cessation of motion.

The action of this switch is made positive and definite from contact to contact by a sustaining device somewhat similar to that

used in the Appleton switch. The principle of its operation is indicated by Fig. 156. When the cam 16 rotates, the bar 19 carrying at one end the roller 21, is moved radially outward from the center of the cam by reason of the peripheral recess 20 having passed from under the roller. As long as the recess 20 does not come under the

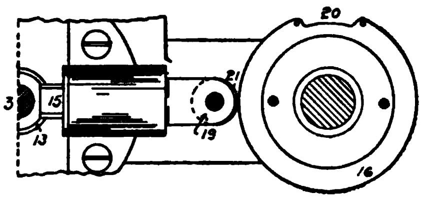


Fig. 156. Achard End Cell Switch, Detail of Sustaining Switch.

roller, the bar 19 must remain in its outward position. A spring (not shown) tends to throw the bar 19 towards the center of the cam, and, whenever the recess is under the roller 21, the bar 19 is sprung inwards, which is its normal position when the switch is at rest.

When the magnet M or M_1 is excited and moves the sustaining switch, the cam 16 is caused to rotate, being geared to the switch screw shaft. As soon as the notch 20 turns from under roller 21, the bar 19 is pushed outward and the end 15 of the bar catches under a shoulder on the stud 13, which has been moved upward or downward the magnet. As long as the bar end is under the shoulder of the stud, the sustaining switch must stay in its operative position. The notch 20 comes under roller 21 after a complete revolution of the cam, which is so geared to the screw shaft that one revolution of the cam takes place for each movement of the switch brush from one contact to the next adjacent one. Obviously, when the notch comes again under the roller, the spring throws the bar again inward, leaving the sustaining switch free to return to its neutral position.

Meyer's End Cell Switch.

An excellent design is that of Dr. Paul Meyer shown in Figs. 157, 158, 159, 160, and 161, and which may be applied to any end cell switch that is operated by a crank or hand wheel.

Fig. 157 is a picture of the complete device, showing its application to a crank-operated, vertical end cell switch. As is seen, the machine consists of a crank, caused to turn by a small motor

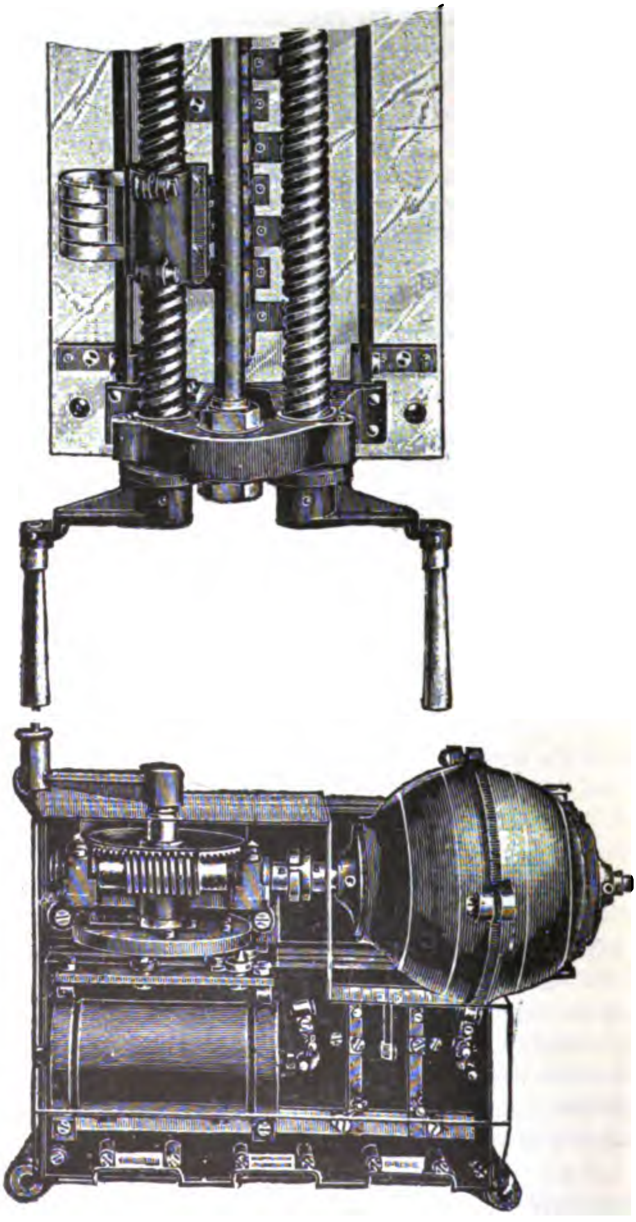


FIG. 157. Meyers End Cell Switch.

which transmits its power to the crank by means of a worm and worm wheel. Below the worm wheel and fastened to the same shaft is a disc. Underneath the disc is a straight bar, on which are mounted three contact points that touch against the lower surface of the disc. Below the bar is a solenoid or magnet, at either end of which is an iron cap, the iron caps being fastened to, and supporting, the contact-carrying bar.

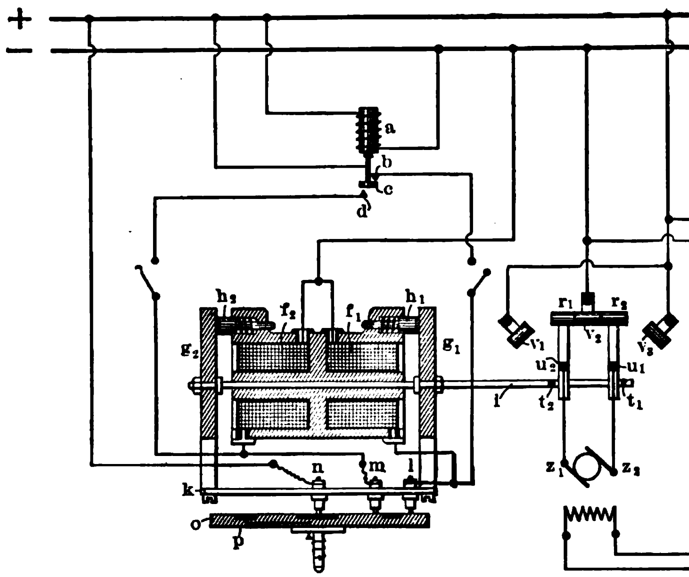


FIG. 158. Meyers End Cell Switch, Diagram of Connections.

Underneath the motor may be seen other movable contacts, actuated by a straight bar which runs underneath the solenoid and which is also fastened to the iron caps at either end of the solenoid.

Fig. 158 shows, diagrammatically, the arrangement; *a* is the voltmeter or potential controlled instrument, which may be in the form of a solenoid or any other desired that is sensitive to small voltage changes. It is connected across the supply circuit as shown, and actuates the contact piece *c*, which touches neither *b* nor *d* when the line voltage is normal. If the voltage rises, *c* closes against *b*, completing the circuit through the winding on the right-hand end of the magnet f_1, while, if the voltage falls, *c* closes against *d*, and the circuit through the winding on the left end of the magnet f_2 is completed.

The iron plates g_1 and g_2 correspond to the end plates or caps at either end of the magnet referred to in Fig. 159. The disc o is shown below the magnet here, as is also the bar k, carrying the contacts l, m, n. The rod i passing through the center of the magnet corresponds to the bar below the magnet in Fig. 157, which connects with the movable contacts r_1 and r_2.

Figs. 159, 160 and 161 show the working face of the disc o, which is made of fiber or hard wood. A circular groove is cut in the face, and a flat copper ring sunk into it. This ring is not continuous but has a short segment removed and the space filled with hard wood, fiber or other insulating material, as indicated by the short black break in the ring.

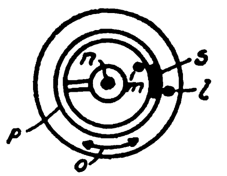


Fig. 159.

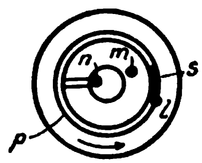


Fig: 160.

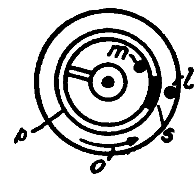


Fig. 161.

Meyers End Cell Switch, Details of Contact Disc.

A small, thin disc of copper is also sunk into the center of the surface of the large disc. The flat ring and the small disc are joined together by a connecting strip as indicated. The entire surface of the disc is smooth and the contacts which rest against it can slip lengthwise across its face and the disc can turn under them.

The action of this machine is as follows:

If the voltage should rise above normal, the voltmeter contact would lift up, connect c and b and pass current through the magnet winding f_1, energizing the right end of the magnet and attracting the iron plate g_1 at the right. This plate will be drawn over to the left, and in moving will shift with it both the contact-carrying bar k and the rod i, which latter is connected with r_1 and r_2. At the time of making contact at c, the disc and the bar contacts are in the position shown in Fig. 159. When the contact bar moves to the left, the bar contacts take the position shown in Fig. 160. l and n are now connected through the copper ring and central disc on the main disc; and in addition to the circuit through b and c, through which current goes to f_1, there is also another circuit made from n to l, which will allow current to flow through f_1 until interrupted, regardless of the position which the voltmeter contact may take.

The motion of the end cap g_1 towards the left also swings contact r_1 over to the left until it touches v_1. r_2 does not move and remains in contact with v_2. The connection is now made through the motor armature in such a manner as to cause a rotation of the worm wheel and disc in the direction shown by the arrow in Fig. 160.

This rotation must continue until one revolution has been completed, which will cause the end cell switch arm to move from one contact over the next one adjacent. When the single revolution is completed, the insulating piece s passes under contact l and opens the circuit through the magnet winding f_1, which, no longer being energized, allows the spring h_1 to push the iron cap g_1 back to its normal position. The motion of the motor should now cease as soon as rotation has carried the insulating piece s around just far enough for contact l to escape it if the contact bar again moves to the left. This stopping point is accurately adjusted by means of an electric brake, made by simply short-circuiting the motor armature, which is done when contact r_1 comes against v_2, which latter is already in contact with r_2.

It is seen that the three contacts l, m, and n are not in line, but l and m are spread or staggered, the distance of this spread being the length of the insulating piece.

If the pressure across the line should decrease, contacts c and d would close; f_2 being energized, the contacts all move toward the left, and the circuit through f_2 made through m and n, the former now resting on the copper ring. Also r_2 moves over to v_3 and the motor armature is connected through them to the mains in a manner opposite to that in which it was connected when the magnet f_1 was energized; consequently the action takes place in a reverse direction, the performance being in every other respect identical in the two cases.

The Schneider switch depends for the positiveness of its length of travel on jumping a given distance when set in motion, and not on the continuous action of a screw thread or gear, which must make a definite number of rotations each movement. This switch is shown in Figs. 162 and 163.

Fig. 162 is a plan, and 163 an elevation.

In the figures, A is the moving screw; B a hand wheel for use when desired; G a motor on the opposite side with its armature keyed on to the screw shaft; C is a bar having notches, n, n, n, n, cut in it equally spaced along its length. When the catch T, at

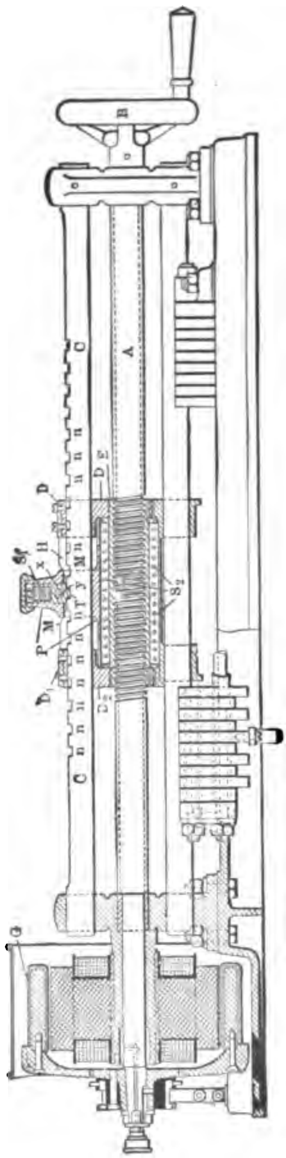


FIG. 162. Schneider's End Cell Switch, Elevation.

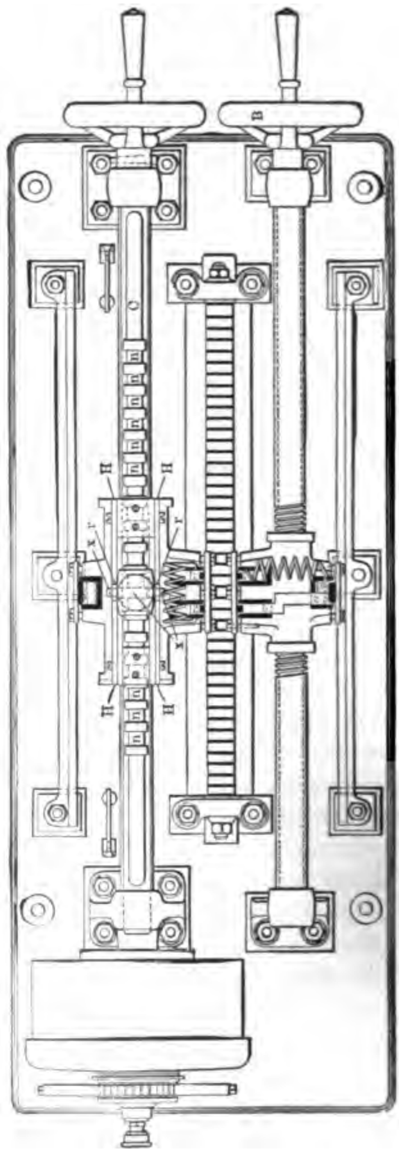


FIG. 163. Schneider's End Cell Switch, Plan

the end of piece X (Fig. 162), is in a notch, the moving contact registers with one of the contact points connected to the end cells. Surrounding the screw is the sleeve nut E, which is fastened to the two guides, D and D_2. These latter also surround the notched shaft C.

Attached to each side of the upper portion of the guides, and joining together D and D_2, are the flat bars H, H, having a narrowed or recessed portion, the thinnest point being just beneath the small rollers *r*, *r*, and directly above a notch *n*, as shown.

When the screw rotates the nut travels, moving with it the guides and the bars H. The only connection, however, between the positively moved parts and the part P, is through the spring S_2, which is compressed when D moves and tends to urge P in the same direction, though D may travel a considerable distance in either direction while P remains stationary.

P is held in position and restrained from moving by the tongue or pawl T, which forms the end of the piece X, and engages in a notch on C. X is pressed always against the notched bar C by the small spring S_1.

Passing through X is a short axis *y*, which carries at its ends the small rollers *r*, *r*.

When the motor is started the screw A rotates, moving with it the nut D, P meantime remaining stationary and the spring S_2 becoming compressed. As H, H move with D, the beveled portions of these bars pass under the rollers *r*, *r*, raising them and Y.



FIG. 164. Bijur End Cell Switch.

When either of the points M has come under the rollers *r*, *r*, the piece X has been lifted sufficiently to disengage the pawl T and the compressed spring S_2 throws P along the same direction as traveled by E and D, and it overtakes them, the rollers running again over the hollowed part of the bars H, H, and allowing the pawl T to

catch into the next adjacent notch *n* on bar C. The end cell switch contact arm being directly connected to P, the movement from one contact to the next is positive and exact.

The motor may be started by a hand switch, or the device may be made completely automatic by applying a contact voltmeter or solenoid to close or open the motor circuit.

The Bijur switch is shown in Fig. 164. Fig 165 is a diagram of the connections. Referring to the diagram, it may be seen that the switch comprises a motor driving a screw shaft S through a

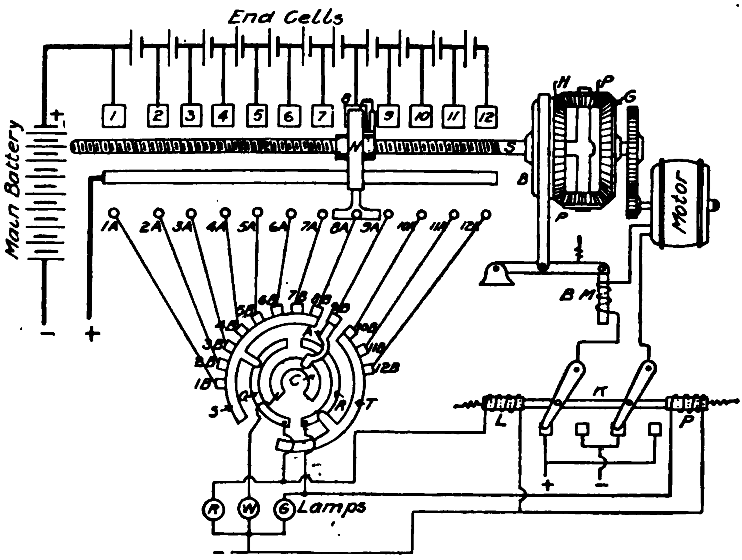


FIG. 165. Bijur End Cell Switch, Diagram of Connections.

set of gears, with an insulated nut upon the shaft carrying the contact brush N, which makes connection from the various contacts to the bus bar.

The driving gear is driven by the motor shaf' and engages with two bevel pinions, P, P, running loose upon the arms of a T-shaped extension of the screw shaft S. These pinions also engage with a bevel gear H which runs loose on the screw shaft and has a drum extension B adapted to engage with a strap brake. This brake is applied by an electromagnet BM, the winding of which is in series with the motor armature.

When the motor is energized by the controller, current passes

through it and revolves the armature in one or the other direction. This current simultaneously applies the brake to the loose gear, holding it still. The motion of the motor gear is then transmitted through the pinions to the screw shaft, revolving it at one-half motor-gear speed and thereby moving the brush. When the brush reaches the contact for which the controller is set, the motor circuit is automatically opened and the brake is released. Due to its momentum, the motor continues to revolve, but as the brake has released the loose gear, it simply revolves about the shaft and the rotation of the screw shaft stops. By proper relation of gears and pitch of screw, the brush may be caused to travel at any desired speed.

The controller comprises a series of auxiliary contacts mounted on the switch, one opposite to each main contact, and a corresponding series of contacts on the switchboard, connected by the control wires to the auxiliary switch contacts. The controller also operates a solenoid switch K which closes the motor circuit and determines the direction of the motor rotation. This switch is operated by magnets L and P.

The handle of the controller is attached to a shaft or drum carrying two segments S and T which sweep over the series of controller-wire contacts, and which connect with two stationary segments Q and R by means of the inner radial projections shown.

The shaft also carries a contact finger A, which is located between the adjacent ends of segments S and T, and adapted to make contact with the innermost stationary segment C and the control-wire contacts. The figure shows the switch moving to the right and controller set to stop the switch at contact 9. In this position, current is flowing from the positive bus bar to the control brush on the auxiliary switch contact 8A, thence over control wire to controller contact 8B, to segments S and Q, to solenoid L and to the negative bus bar. This controls the motor rotation and its direction. When the brush reaches contact 9, this circuit will be broken at 8A, switch K will open, and current to the motor will no longer flow. Also brake magnet BM will not be energized, and the brake B released. Motion of the screw will immediately stop, although the motor armature will continue to rotate a short time, due to its momentum.

The control brush, which makes contact with the control con-

tacts, is T-shaped, so that circuit will not be opened until the main brush N fully registers with main battery contact 9.

If the controller were set so that finger A were on a contact, corresponding to a main contact to the left of its initial position, segments T and R and solenoid P would be in circuit, switch K would be drawn to the right, and the motor would run in the other direction until the brush reached a position corresponding to that of finger A.

It is obvious that the controller position is not in any way dependent on the switch position. Hence, if the controller be set for any position and some other setting should later be decided upon, it is not necessary to wait for the brush to reach the contact first called for. The controller may be reset as much as desired while the switch is in motion, and the brush will follow the setting and finally rest upon the contact at which the controller is left.

For indicating the position of the brush to the switchboard attendant, three indicator lamps are used, set in a row on the board. The center one is white, the left-hand one red, and the right-hand one green. When the brush position corresponds to that of the controller, the white lamp is lighted; if the controller is moved to the left, the red lamp is lighted and remains lighted until the brush reaches the contact for which the controller is set; and if the controller is turned to the right, the green lamp is lighted.

As shown in figure, the brush is to the left of the controller position, and circuit is closed from the positive bus through the control brush to auxiliary contact 8A, thence through the wire to contact 8B, and via segments S and Q to red lamp X, and thence to the negative bus bar, lighting the red lamp. When the brush reaches contact 9 the above circuit is opened, and another circuit is closed from the control brush to contact 9A, thence to contact 9B, to finger A, to segment C, and through white lamp W to the negative, lighting the white lamp, which burns while the switch is at rest.

If the brush were to the right of the controller position the green lamp Y would be lighted through segments T and R to the negative bus bar.

A hand wheel is provided for manual operation of the switch when necessary, as shown at the right of Fig. 164. To prevent opening the circuit, the brush N is usually divided, one main

portion being the width of a single-contact block, and the other connected to the main brush through a resistance, the width across the two brushes being a little less than the width of one block plus one space.

This prevents short-circuiting of the end cells as the brush travels over the contacts.

The main brush is laminated copper, and is arranged at an angle of a little less than 90° to the line of travel. This prevents grooving of the contact blocks and bus bars by the laminations.

Another form of mechanically operated end cell switch controlled from a distance is that of the *Société Alsacienne des Constructions Mécaniques,* the principles of which are illustrated in Fig. 166.

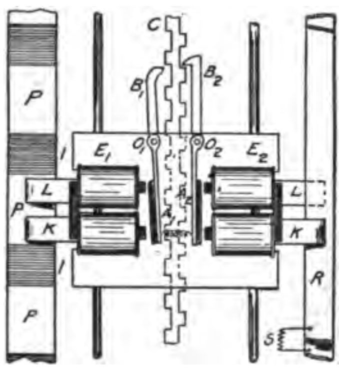


FIG. 166. End Cell Switch of Société Alsacienne des Constructions Mécaniques, Detail.

P, P, P, are contacts. R is the main bus bar. An auxiliary bus bar is placed behind the main bus bar, and the two connected by resistance S. K is the main brush and L is the auxiliary brush, contacting respectively with the main and auxiliary bus bars. E_1 and E_2 are electro-magnets which are energized by push buttons on the switchboard, the circuits from which connect with the magnets.

The notched piece C has a reciprocating motion in the direction of its length, the distance of its movement being equal to the distance between centers of the contacts P, P, P. This motion is given piece C by an eccentric on a rotating shaft. The pawls B_1 and B_2 are adapted to work in the notches in reciprocating piece C. Obviously, if magnet E_1 be energized and pawl B_1, which is

attached to magnet armature A, is by the resulting movement of A_1 made to engage in the notches of piece C, the brushes will be moved downward a distance equal to the travel of C, which is the distance from one contact to the next.

Conversely, if magnet E_2 be energized by closing a switch or push button, the brushes will be moved upwards.

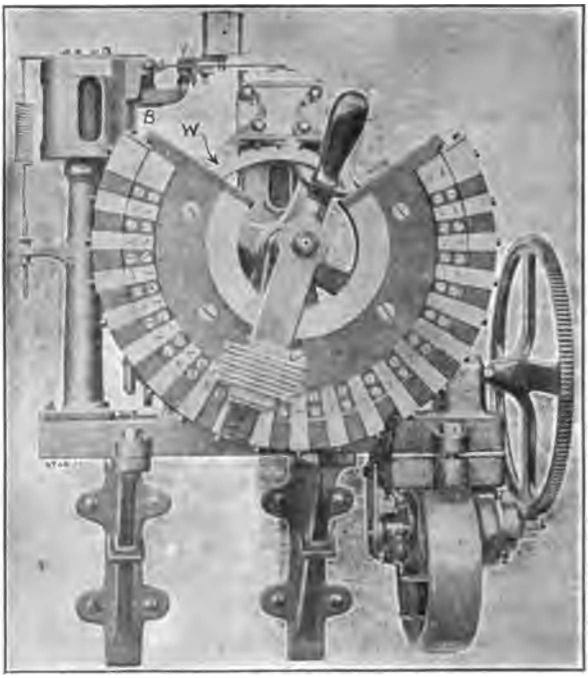


FIG. 167. Thury End Cell Switch.

Fig 167 shows an end cell switch operated by the *Thury* automatic controller. The pawls shown are oscillated continuously by a motor, moving through an angle equal to the angular spacing of the contacts. Tappets, operated by a magnet B, cause one or the other pawl to engage with the notched wheel W and produce rotation, the direction being fixed by whichever pawl engages.

All automatic end cell switches having slide brushes must be provided with a safety device of some kind to prevent jamming of the traveling nut on the screw when the end of its movement has been reached, at either end of the screw. One form is shown

in Fig. 168. N is the traveling nut moving along the screw shaft. Fastened thereto are the pieces D and E, through which pass the adjustable screws S and S.

The current to the motor which rotates the screw passes through the arm B of the bell crank-lever to the clip C, and on through the rest of the circuit.

As N approaches the end of its travel, S presses against A and causes B to rise and leave the clip C, thus opening the circuit and

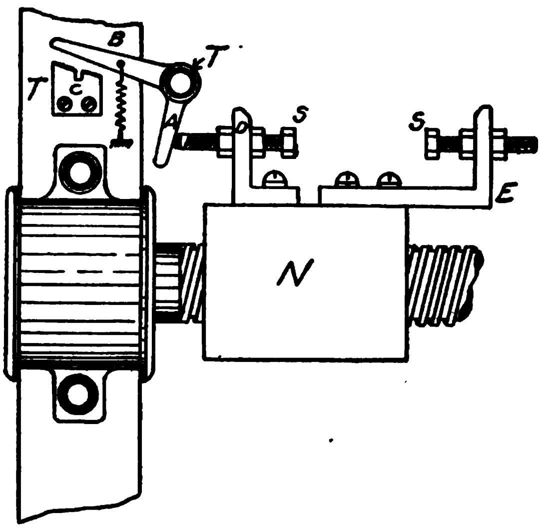


FIG. 168. Safety Limit Stop.

stopping the driving motor. It is impossible for N to travel past a point which is fixed by adjusting S.

*Lyndon Switch.**

This switch has no sliding contacts, but a solenoid-actuated contacting switch is attached to each end cell connection. Its chief object is to reduce the cost of the end cell switch, eliminate the end cell copper, and to increase the speed of working.

Figure 169 shows a diagram of the main connections. There is one main contactor for each end cell, but one less auxiliary contactor than there are end cells.

The operating windings of the contactors are energized from the line, or from any convenient source of supply, through a controller.

* Amer. Pat. 782436 to Edward Lyndon.

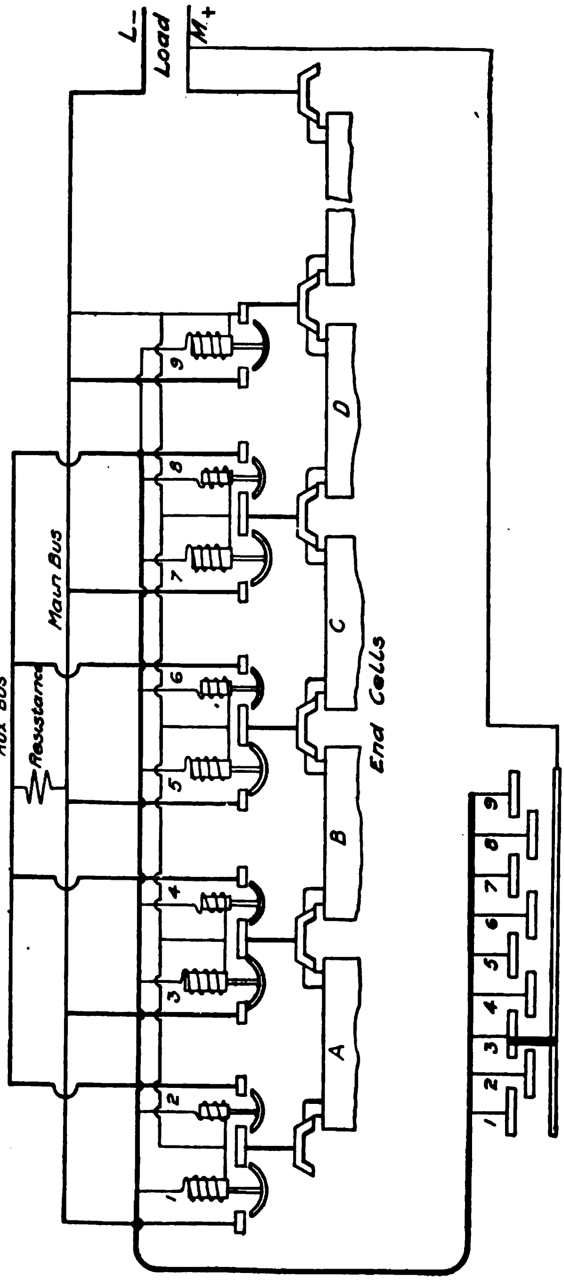


FIG. 169. Lyndon End Cell Switch.

In the diagram the controller is shown in horizontal form. In practioe however the bars and contacts are circles or arcs laid out around a central pivot, about which the controller contacts may be revolved.

The controller consists of one contact for each main and each auxiliary contactor and a bus bar to which any contact may be connected by means of a moving brush. Each contact point on the controller is connected to one terminal of the magnet winding corresponding, the wires being bunched in a cable as indicated. Thus, contact 1 of the controller is connected to one terminal of magnet 1; contact 2 to one terminal of magnet 2.

The terminals of the magnet windings not connected to the controller contacts are all joined together and connected to one side of the system, while the controller bus bar is connected to the other side.

In the diagram L, M represents the circuit supplied from the battery.

In the positions shown, the magnet winding of contactor 3 is energized through contact 3 of the controller, so that end cells B, C, D are included in the circuit. If it is desired to add one more end cell, the controller brush is moved towards the left; before the brush leaves contact 3 it engages contact 2, thus energizing auxiliary contactor 2. In this position both the auxiliary contactor 2 and the main contactor 3 are energized at the same time, and end cell A is connected to the auxiliary bus directly, and thence to the main bus through a counter cell or through a resistance.

The resistance prevents short-circuiting the end cell A while the contactors 2 and 3 are both energized. As the controller brush moves towards the left it leaves contact 3, but still engages contact 2, and contactor 3 is de-energized and opens; the entire battery current passes through auxiliary contactor 2, thence to the auxiliary bus, then through the resistance to the main bus bar.

Up to this point the voltage of the end cell A has not been added to the main circuit, as the drop through the resistance equals the voltage of the added cell A.

As the controller brush continues to move to the left, it engages contact 1 before it leaves contact 2, thus energizing contactor 1; this connects end cell A directly to the main bus bar and this cell is then added to the circuit; the controller brush continues to

move to the left until it engages contact 1 only, de-energizing contactor 2, and allowing it to open.

The contactors are mounted in pairs, and in the case of large installations, the pairs of contactors for each end cell may be mounted in acid-proof casings and erected directly above the end cells. In this way, the only end cell copper required is the one main bus bar and the auxiliary bus bar.

The controller wires from the contactors are carried out to the switchboard where the controller is mounted. This instrument is both a cell indicator and controller, and is designed so that the brush cannot be moved at a speed greater than that required for the contactors to make the necessary movements.

This speed however is much greater than it is possible to obtain with motor-driven, sliding contact switches.

With this switch a semi-automatic, distant control has been devised, it being so arranged that the controller may be located near the battery and operated by means of a small motor, the actual control being from any distant point. This feature involves running only three wires from the motor-operated controller to the point of distant control.

From the diagram it will be seen that the maximum potential across the various contactor terminals is that due to the charging voltage of one cell only,—less than three volts. The circuit is never broken in varying the number of cells, and for this reason the movement of the contactor may be small in comparison with contactors of standard design, thus reducing the magnet winding and eliminating the necessity of auxiliary breaks across the contactor terminals.

The auxiliary contactors need be only of sufficient capacity to carry the charge or discharge current for a fraction of a second, so that these may have just sufficient area to prevent burning the contacts during the very short time they are in circuit. Any voltage drop across the terminals of the auxiliary contactors is beneficial, as the greater this drop the less the resistance necessary between the main and the auxiliary bus bars.

End Cell Switch Indicators.

When end cell switches are operated by motors, it is desirable to know whether the brush has passed fully on to the proper cell contact and stopped without under- or over-traveling. For this purpose end cell indicators have been devised which show at the

switchboard the position of the brush. The most commonly used indicator is a straight scale over which a pointer travels, the motion being communicated from the end cell switch by means of small shafting and gears. This is a cumbersome appliance, but it is reliable and positive in its action.

A simpler and cheaper device which is also satisfactory, is made up of a small sprocket wheel at the end cell switch, and a sprocket chain passing over it connected to a sprocket wheel on the indicator, which is also engaged by a sprocket chain. The chain is not continuous from the switch wheel to the indicator wheel, but the two short lengths are joined together by steel-wire rope, $\frac{3}{16}''$ in diameter, which can be turned over small guide pulleys in any direction. Turn buckles are inserted in both sides of the rope, so that accurate adjustment of the indicator pointer with relation to the position of the end cell switch contact arm is possible.

In the Bijur and the Lyndon switches, the hand controller points to the contact on which the switch brush rests, and thus serves the purpose of indicating the switch position.

CHAPTER XXIX.

END CELL CONDUCTORS.

THE conductors connecting the battery and end cells to the switchboard and end cell switches should have sufficient area for the current density not to exceed 1200 amperes per square inch, when the battery is discharging at its maximum rate.

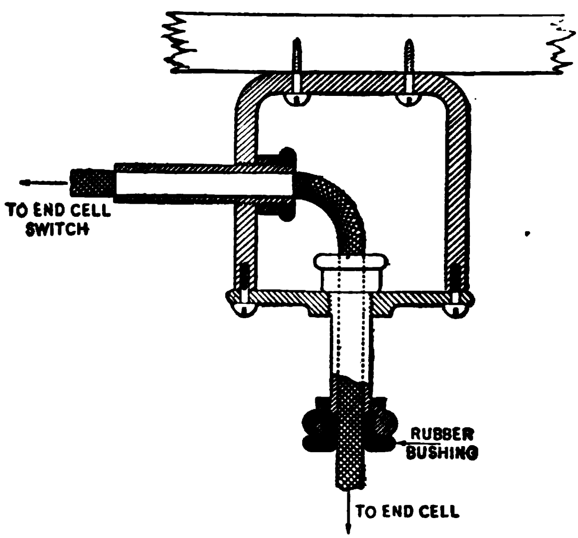


FIG. 170. Conduit Outlet for End Cell Connections.

When installations are of small capacity; the end cell conductors are made up of insulated copper wire or stranded cable; these conductors are carried to the end cell switch terminals and connected thereto.

In many instances, the insulated wire or cable is simply run on insulators from the battery to the end cell switches located outside the battery room. When this is done, however, the insulation will soon deteriorate from the destructive action of the acid fumes; when the insulation becomes impaired, the bare copper is then

exposed to the action of the acid. To prevent this, the wires, when of small size, are sometimes laid in molding, which is painted with some acid-proof paint, such as black asphaltum.

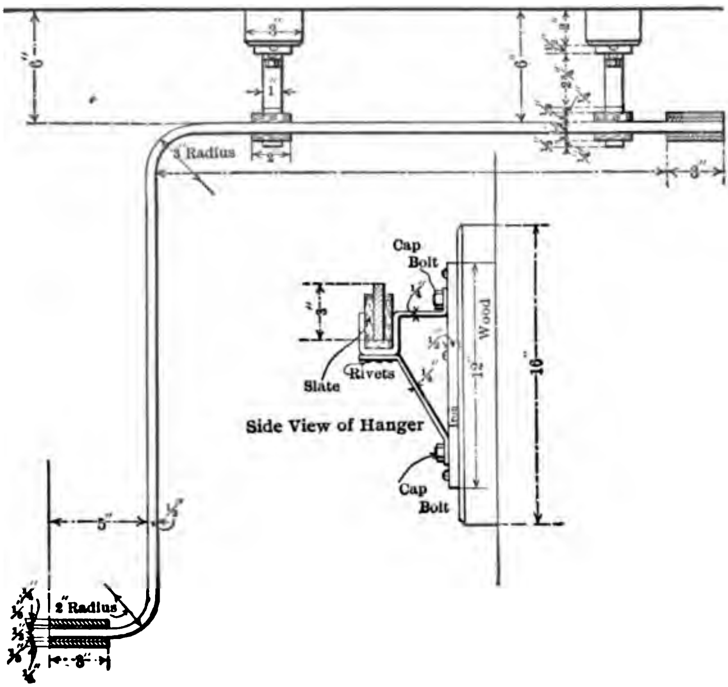


FIG. 171. Method of Erecting End Cell Conductors.

A better method, however, and one that is applicable for conductors of considerable size, is the use of iron conduit, which forms an effective and permanent protection for the cable.

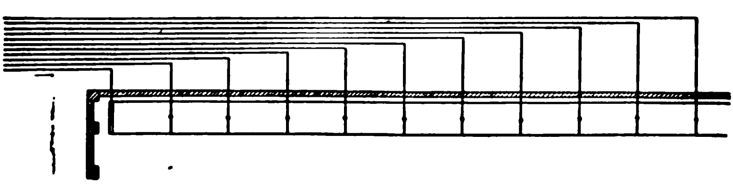


FIG. 172. Diagram of End Cell Connections.

When the conduit is used, it is better to have a separate duct for each end cell conductor. Each conduit outlet is situated directly over an end cell where the cable leaves the outlet box, and the open-

ing is provided with a soft rubber compression bushing to prevent any acid fumes from getting into the conduit, as shown in Fig. 170.

If the maximum discharge of the battery exceeds 1000 amperes, cable should not be used, rolled copper bars being more satisfactory. No attempt is made to insulate these, but they are either lead-coated or heavily painted with asphaltum paint to prevent any corrosion by acid vapor. They are usually supported by

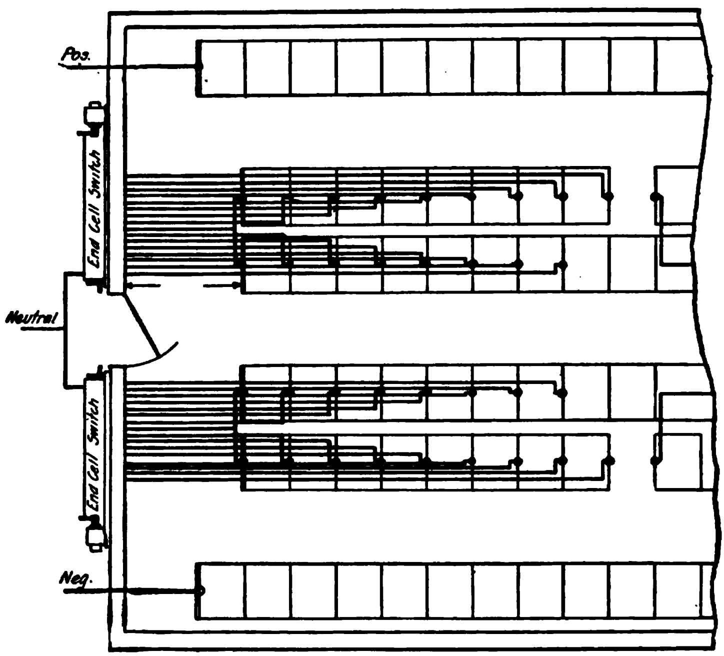


FIG. 173. Diagram of End Cell Connections.

hangers suspended from the ceiling. The hangers are provided with slate or porcelain blocks, which form an insulating support. Fig. 171 shows the method of supporting bar conductors.

The question of end cell copper has considerable bearing on the layout of the cells in the battery room. If the battery be of small capacity, the number of end cell conductors comparatively few, and if the end cell switch be located near the battery room, the layout demands no special attention in this regard. If, however, the capacity of the battery is such that copper bars must be used, it is

then essential that the end cells be so arranged as to allow a minimum length of copper bar from the end cells to the end cell switch, and to have as few bends in the conductors as possible. Fig. 172 shows the usual arrangement for 125-volt installations having eleven end cells. For higher voltage equipments with a large number of end cells, the most economical grouping is that shown in Fig. 173.

Where bar conductors are used, considerable accuracy is required in setting up the cells.

The bars are bent and drilled before shipment, consequently, if the tank and lead bus bar spacing are not exactly correct, the bolt

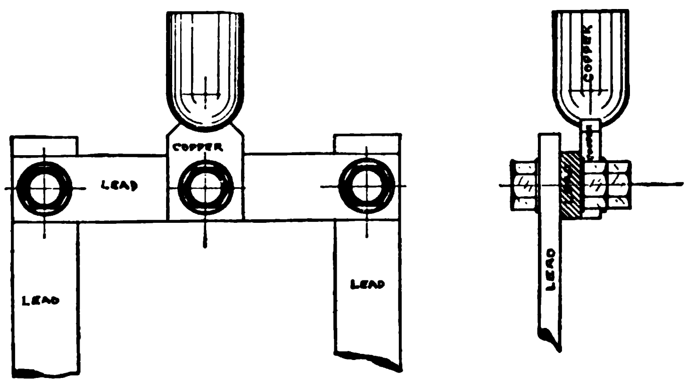


FIG. 174. Lugs and Connections for Cell Connections.

holes will not register with each other and the separate runs of copper will not be parallel.

The cost of construction will vary, of course, with the amount of bending, drilling, etc., necessary, but an average figure of from 32 to 40 cents per pound will generally cover cost of bar work complete and erected.

Connections from end cell conductors to end cells are made with lugs where wire and cable are used. In the case of bar work, the conductor is bolted directly to the reinforcement of the lead bus bar.

Fig. 174 shows method of connecting wire or cable conductor to end cells, the cable being soldered into the lug, and this lug bolted to the cross bar between the two terminal straps.

All lugs, nuts and studs should be lead-covered.

CHAPTER XXX.

BOOSTERS.

BOOSTERS are dynamo-electric machines which are placed in series with the battery or with the supply line to the bus bars across which the battery is connected. The function of these machines is to generate an electro-motive force assisting the flow of current from the main generator to the battery, or a voltage opposing that of the main generator and assisting the battery to discharge. This added or subtracted voltage may compensate simply for the drop due to the internal resistance of the battery and connections, or the change in battery voltage as the state of charge is changed, or both.

Boosters may be hand-controlled or automatic in their variation of voltage, to meet changing conditions of battery charge or drop.

The hand-regulated boosters are used generally for charging batteries, and occasionally for assisting battery discharge.

Self-regulating boosters are for the purpose of causing instantaneous charge and discharge of the battery on systems supplying energy to loads which fluctuate widely and rapidly in the power demand. With a battery and automatic booster, the generator load is kept practically constant, as any sudden demand in excess of the constant generator output is met by the instantaneous production of a booster voltage to cause discharge, the voltage being of just the proper value to produce a battery output equal to the excess of the load above the generator constant load. Conversely, the reduction of the external load, below the constant generator output, is attended by the production of a booster voltage that sends current into the battery, the booster voltage being just high enough to cause a charging current to flow which represents the difference between the external load and the normal generator current. By this means the generator load is kept constant, within a small percentage, and the generating equipment is relieved of the sudden shocks and injurious effects of rapidly fluctuating loads,

and can be operated more economically than if the battery and booster were not present to act as a "buffer."

In the analyses of the different systems which follow, it is assumed that the open-circuit battery voltage is equal to the generator voltage when delivering its normal output.

Also, unless otherwise stated, the open-circuit battery pressure is taken as 2.1 volts per cell. This value is approximately correct for cells having antimony alloy plates or grids. For pure lead grids or plates the open-circuit voltage may be as high as 2.12 volts per cell, and all numerical computations must take in consideration the character of plate and its open-circuit voltage.

The maximum voltage on charge is taken as 2.6 volts. Pure lead grids or plates give a maximum voltage = 2.7 volts.

The minimum voltage, on discharge, when the battery is nearly exhausted and delivering maximum current, is taken as 1.65 volts per cell.

The virtual internal resistance of the battery is used in all the succeeding computations. This quantity varies for the state of charge of the battery, and the length of time charge or discharge is prolonged. This quantity as used in these formulæ is understood to mean the value of the internal virtual resistance after 70 seconds of charge or discharge, when the battery is not less than 50 per cent nor more than 80 per cent charged. After about 70 seconds the battery drop, which increases continuously for about this length of time, reaches a practically constant value.

When the battery voltage falls to 1.65 volts per cell on discharge, this means a drop of 0.45 volts per cell below normal, open-circuit, voltage (assuming 2.1 volts as the floating pressure). Hence, for this particular condition, R must be taken as equal to $\frac{0.45\ \text{N}}{\text{Battery dischg. current}}$, N being the number of cells in the battery and R the virtual internal resistance.

"Regulation" means the percentage increase in generator current to produce a full discharge of the battery when the state of charge is such that the terminal voltage falls to 1.65 volts per cell.

In computing the size of self-regulating boosters, and their driving motors, it must be remembered that, generally, the maximum current output lasts a few seconds only, or a minute or two at most. Therefore the only basis for fixing the size of the machines

is the maximum currents they will commutate without flashing. The heating factor may in most cases be neglected, as the time integral of the booster output is very small compared to the maximum momentary output. In the examples given, the booster capacity is taken arbitrarily at 40 per cent of the maximum output. In Chapter XXXVI, however, it is shown how in many instances this may be reduced to 20 or 25 per cent.

As will hereafter appear, there are numerous types of automatic boosters. They may be classified as *self-excited*, *separately excited*, and *externally controlled*.

They may all be generally classified as reversible and non-reversible, according to whether the current passes through the booster armature in either direction, being in one direction for charge and in the opposite direction for discharge, or whether it passes, in one direction only, continuously through the armature.

The non-reversible booster is called also the "constant current," due to the fact that the current through its armature is kept nearly constant, while, with all reversible boosters, the current through the armature fluctuates greatly.

In computing booster and battery capacities it must be remembered that, for regulating work, the current for the driving motor must be supplied from the battery. This increases the size of booster and motor above the theoretical capacities based on the discharge to the line, as is shown more in detail in Chapter XXXV.

CHAPTER XXXI.

MANUALLY CONTROLLED BOOSTERS.

THE only type of manually controlled booster in general use is the charging or so-called shunt booster, which is used to augment the generator voltage when charging a battery, which may later carry the entire load alone, or be discharged in parallel with the generator assisting it to carry a load peak. Consider the case of a 110-volt circuit on which is a battery to carry the load when light, or to work in parallel with the generator on heavy load. The voltage at the end of discharge will be 1.8 volts per cell, and therefore $\frac{110}{1.8}$ = 61 cells will be required. The voltage per cell at the end of charge, however, will be 2.6, and the total voltage $2.6 \times 61 = 159$ volts, which is 49 volts more than the generator pressure, and this is the voltage that the booster will have to furnish.

This machine may also be used reversibly—that is, give an electro-motive force to assist the battery to discharge—when excited from the bus bars, and provided with a reversing rheostat or field reversing switch. In this case it will assist the battery to discharge when the direction of the field magnetization is changed. When so used, no end cells are necessary, but the booster must be run continuously during the entire period of discharge. On a 110-volt circuit, 56 cells will be sufficient with a reversible booster. Voltage to charge fully is $56 \times 2.6 = 146$, or 36 volts above generator voltage. Minimum voltage of discharge $= 1.8 \times 56 = 100$ volts, or 10 volts less than that of the line. Therefore, the booster need give only 36 volts maximum, and is called on to add 10 volts to the battery voltage toward the end of battery discharge. In this case, the booster voltage is only $\frac{36}{49}$, or three-fourths that required in the preceding case; five cells less of battery are necessary and the end cell switches and leads are eliminated.

The machine will be much larger, however, than it would be if used only for charging, because the discharge current is invariably

greater than that of charge, and the current-carrying capacity of the armature must be great enough to take care of the heaviest currents.

Fig. 175 shows the usual connections of a non-reversible shunt booster and battery system.

G is the main generator, B the booster, S_1 and S_2 are double-pole single-throw switches, S_3 a double-pole double-throw switch, and S_4 a battery end cell switch.

To charge, S_1 and S_2 are closed; S_3 is closed downward and S_4 put on the outermost point. Part of the generator current will go into the line and part through the booster into the battery. Charging current is adjusted by means of rheostat *r*, which varies the voltage of booster.

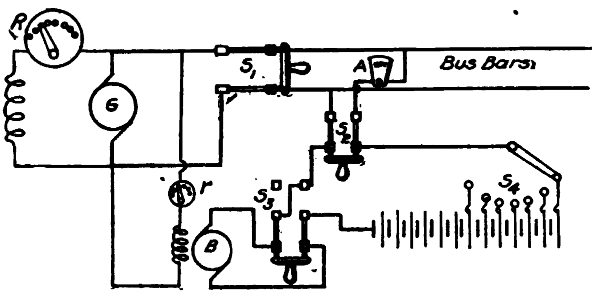


FIG. 175. Connections for Shunt Booster.

To discharge, throw S_4 to first point on end cell switch. Next, S_3 should be thrown over to the upper clips. The battery is then in parallel with the generator with all end cells cut out. As the voltage of the battery falls, end cells are cut in by switch S_4. When S_1 is opened, the battery supplies the entire load.

In the case of a reversible booster, the booster field is connected across the bus bars and a reversing switch or rheostat is used, the end cells and S_4 being omitted.

The size of booster required varies with the voltage of the system, and the maximum rate of current flow. If the maximum load lasts only a few minutes, it may be considered as overload and the machine designed for a normal load, less than that represented by the maximum.

The maximum voltage should be equal to $2.7 \times N$, where N is the number of cells in series. The voltage of 2.7 per cell is sometimes necessary in giving the battery an overcharge.

The power of the driving motor is seldom made equal to the capacity of the booster. Since the maximum booster voltage and current never occur simultaneously, the maximum capacity is never reached, and there is no need of making the motor sufficiently large to handle the rated capacity of the booster.

If the booster is reversible, the greatest driving power will be required when the maximum discharge is given out and the voltage of the battery lowest. For instance, if the normal charging rate is 50 amperes and there are 56 cells in the battery which is connected across a 110-volt circuit, the maximum power to drive when charging would be when the voltage per cell reached 2.6 volts. The booster volts at this time would be $2.6 \times 56 - 110 - 36$ volts. Assuming the current of overcharge to be one-half the normal, the booster output for this condition is

$$\text{Watts} = 36 \times \frac{50}{2} = 900.$$

Motor H. P. $\dfrac{900 \times 1.34}{.75} = 1.61$ H.P., .75 being the assumed efficiency of the booster. If, however, the maximum discharge rate is 180 amperes, and the battery voltage is 1.8 per cell, the booster volts are equal to $110 - (56 \times 1.8) = 10$ volts.

$$\text{Motor H. P.} = \frac{10 \times 180 \times 1.34}{.75} = 3.23 \text{ H.P.},$$

which is as large as the motor should be made.

The size of the booster would be $36 \times 180 = 6.5$ kilowatts, unless the maximum amperes flow only for a few moments, in which case the capacity could be somewhat reduced. If the booster were used only for charge, there would be 61 cells in series, making the booster maximum voltage on charge = 49 volts. The capacity would be $49 \times 50 = 2.45$ K.W.

These figures show the increase in size of booster and motor when the former is made reversible, though the computed increase is for the particular conditions given only.

CHAPTER XXXII.

SELF-EXCITED, AUTOMATIC BOOSTERS.

The self-excited boosters that automatically vary their voltages to correspond with the load fluctuations on the external circuit and the condition of battery charge, and cause charge or discharge of the battery as the load changes may require, are the *series*, the *compound*, the *differential* and the *constant current*.

Series Booster.

This was probably the first automatic booster, though, because it is operative only with shunt generators and by reason of its instability in working and the better regulation obtained with present-day types, it has become obsolete.

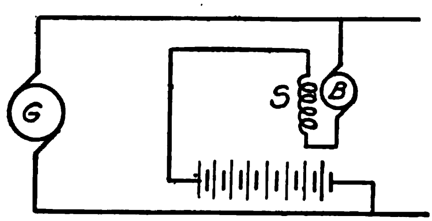


Fig. 176. Connections of Series Booster.

The connections are as shown in Fig. 176. G is the generator, C the battery, B the booster armature connected in series with the battery and having the series field coil S. The external load is connected across the line at any point.

With no current flowing into or out of the battery the voltage of the booster is zero, and the open-circuit battery voltage is equal to the generator voltage when the generator is delivering its normal load. If the external load should decrease, the generator voltage will increase and a small current pass through the booster to the battery. This small current flow energizes the field S and produces a voltage in the booster armature to send current into the battery, which current will increase until the load on the generator reduces its voltage to a point where the electro-motive forces of the system are in equilibrium.

If the external load should increase, the reverse of the foregoing conditions obtains and battery discharge takes place, assisting the generator.

This booster tends to "compound" the battery, that is, to compensate for the change in battery terminal voltage and maintain the line voltage constant with load fluctuations. This system is suitable only for power work.

*The Compound Booster.**

This form of booster is used on railway and power circuits supplying widely fluctuating loads where the batteries serve to

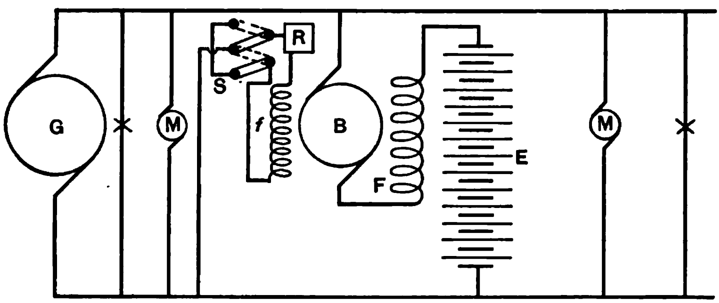


FIG. 178. Connections of Compound Booster.

prevent excessive feeder drop, and assist the power station, relieving the generating machinery from the sudden, heavy, current rushes. Diagrammatically, this system is shown in Fig. 178.

G is a generator, E a battery, B the booster armature, F a series field, *f* a shunt field, R a rheostat in shunt field circuit, M and X the load, and S a reversing switch by means of which the magnetization of the shunt field may be added to or subtracted from that of the series field. The operation of this system is as follows:

Under normal conditions, the shunt field creates voltage in the same direction as the battery voltage, tending to cause discharge. Calling E_0 the generator voltage, V the booster voltage and E_A the battery voltage, $E_0 - V = E_A$, ... (67), when there is neither charging nor discharging current. In this case the generator current equals the external load current. If the load increases, E_0 falls, and $E_A + V$ becomes greater than E_0, allowing the battery to begin discharging. The discharge current, passing through the series coil, produces an electro-motive force proportional thereto,

* Amer. Pat. No. 625099, to J. B. Entz, May 16, 1899.

and acting with the shunt coil, thereby increasing V and increasing $E_A + V$, causing a still more rapid discharge. The battery thus assisting the generator causes the load on the latter to decrease and its voltage to rise again until it attains its normal value.

If the load on the external circuit falls below normal, E_0 rises and current starts flowing into the battery. In this case, magnetization of the series field opposes that of the shunt coil, decreasing V. Then $E_0 > E_A + V$ and the charging current increases until E_0 begins to fall, and comes down to its normal value. These changes are, more strictly, tendencies to change which are checked in their inception.

In order to compute the size and windings of the booster, a load curve is necessary. This, in case of a new plant, may be made up from assumed data, which, with the amount of data available covering operating plants similar to the proposed plant, will usually be sufficiently accurate to use as a basis for computation.

The booster must be able to commutate a current equal to the maximum battery discharge, or $I_x - I_0$, in which

I_0 = generator current.
I_x = current to external load.

Also let

V = booster voltage due to shunt coil at open-circuit voltage of battery.
E_M = generator voltage at no load.
E_A = battery voltage, on open circuit.
h = constant which multiplied by the generator current equals drop in generator e.m.f.
R = virtual internal resistance of battery.
k = volts generated in booster armature per ampere turn on field.
T = number of turns in series field.
N = number of cells in series $= \frac{E_A}{\epsilon}$, in which
ϵ = open-circuit voltage per cell.

The series turns must produce a booster electro-motive force that will just compensate for the change in battery voltage due to the inflow or outflow of current when the battery is in condition of normal charge or when R has its normal value.

Neglecting the current required for the driving motor, the bat-

tery current at any time is $I_x - I_0$, and the drop or increase in battery voltage is $R(I_x - I_0)$.

The ampere turns in the series field at any time $= T(I_x - I_0)$ and consequently the booster voltage due to the series turns $= Tk(I_x - I_0)$. From the condition that the booster voltage must compensate for battery voltage drop

$$Tk(I_x - I_0) = R(I_x - I_0). \quad \ldots \quad (69)$$

Whence

$$Tk = R \quad \text{and} \quad T = \frac{R}{k}. \quad \ldots \quad (70)$$

These equations assume a straight characteristic of the booster. This is not exactly true but is sufficiently correct for all practical computations.

The generator voltage must, at all times, be exactly equal to the battery voltage plus the booster voltage.

Generator voltage $= E_M - I_0 h$.
Battery voltage $= E_A - R(I_x - I_0)$.
Booster voltage $= V + Tk(I_x - I_0)$.

The equation of electro-motive forces, therefore, is

$$E_M - I_0 h = E_A - R(I_x - I_0) + V + Tk(I_x - I_0). \quad (71)$$

Whence

$$I_0 = \frac{E_M - V - E_A + I_x(R - Tk)}{R + h - Tk}. \quad \ldots \quad (72)$$

For normal conditions of battery charge, $R = Tk$ and equation 72 reduces to

$$I_0 = \frac{E_M - E_A - V}{h}. \quad \ldots \quad (73)$$

For condition of maximum battery discharge at time of battery exhaustion and volts per cell = 1.65 volts,

$$R = \frac{N \times 0.35}{I_{X\,MAX} - I_0}, \quad \ldots \quad (74)$$

and this value of R must be adopted and substituted in equation 71 to find I_0.

Also note that the numerator 0.35 is found by deducting the minimum voltage on discharge from the normal, open-circuit voltage of the battery. If the open-circuit voltage is 2.10 and the mimimum is 1.60, then for condition of battery exhaustion

$$R = \frac{0.50 \times N}{I_{X\,MAX} - I_0}.$$

Obviously, for the change in the value of R, I_0 does not remain at its normal value, but becomes considerably greater for high values of R than when the battery is charged. Also, instead of remaining constant for a given value of R, I_0 changes slightly with change in external load, as shown by the factor $I_x(R - Tk)$ in equation 72.

All the foregoing equations are based on the assumption that the shunt coil is connected across the line and subjected to the constant voltage E_A.

If the coil f is connected across the battery, the shunt coil voltage will vary with that of the battery and

$$V = \frac{V(E_A - R(I_x - I_0))}{E_M}. \tag{75}$$

Substituting this value in equation 71 and solving for I_0,

$$I_0 = \frac{E_M - E_A - \frac{VE_A}{E_M} + I_x\left(\frac{VR}{E_M} + R - Tk\right)}{R + h - Tk + \frac{VR}{E_M}}. \tag{76}$$

For $Tk = R$ this equation reduces to

$$I_0 = \frac{E_M - E_A - \frac{VE_A}{E_M} + I_x\frac{VR}{E_M}}{h + \frac{VR}{E_M}}. \tag{77}$$

Comparing this with equation 73 it is clear that the regulation is better with the shunt coil connected across the line, as I_0 is a constant and independent of the changes in external load, when R is constant, while equation 77 shows that with the shunt coil connected across the battery, I_0 varies with the external load.

The factor $\frac{RV}{E_M}$ is, however, usually very small as compared with the other quantities.

If V be made small, E_A more nearly approaches $E_M - I_0h$, and the size of the machine is kept down. If V be made large the size of booster is increased, but the number of cells decreased.

Generally, V at normal voltage of battery should be small — 0 to 5 volts. The shunt coil, however, must be capable of producing an e.m.f. high enough to maintain the equality of equation 73 when E_A is at its mimimum, and also to preserve the equality of

$$E_M - I_0h + V = E_A \tag{78}$$

when E_A is at its maximum and the field is reversed in direction, the booster adding its voltage to that of the generator. The maximum battery voltage, on regulation, seldom exceeds 2.4 volts per cell, or about 20 per cent increase above the normal, open-circuit voltage. Therefore the maximum battery voltage $= 1.20\ E_A$ and the maximum booster voltage due to the shunt coil must be $0.20\ E_A - V$. Maximum booster voltage due to the shunt coil when battery voltage is a minimum is $0.175\ E_A + V$, because the drop when the battery voltage is minimum is 0.35 N, or 17.5 per cent of the normal battery voltage. These figures vary, of course, with the floating voltage of the battery and the minimum and maximum voltages actually obtained.

These data fix the shunt winding and, together with equation (78), the size and resistance of the rheostat. This latter should be capable of varying the shunt coil pressure from 0 volts to maximum by steps of not over 2 volts each.

The size of the motor is fixed by the maximum product of booster voltage multiplied by the battery current, both being taken at the same instant. This product is a maximum when the battery is at its lowest voltage and discharging its maximum current.

Assuming 1.65 volts per cell as a minimum when discharging maximum current, and 2.1 volts as the open-circuit pressure per cell.

$$E_{A\ MIN} = \frac{E_A \times 1.65}{2.1} = 0.786\ E_{A\ NORMAL}.$$

The voltage then of booster when discharging $I_{MAX} = 0.214 \times E_A + V$.

Watts $= I_{MAX}\,(0.214 \times E_A + V)$.

Since the heavy current discharges are only momentary, the size of booster and driving motor need only be sufficiently large to commutate the maximum currents.

This form of booster can also be connected for normal operation with the shunt coil pressure in opposition to the battery e.m.f., in which case

$$E_M - I_0 h = E_A - V \qquad (79)$$

and the required number of cells in series is greater than when connected with V opposing the generator electro-motive force.

The relations of the various quantities can easily be worked out from the equations given by making the proper substitutions of signs. In this case, if *f* be connected across the battery,

$$I_0 = \frac{E_M + \frac{VE_A}{E_N} - I_x\left(\frac{RV}{E_N}\right) - E_A}{h - \frac{RV}{E_N}} \tag{80}$$

The equation shows that connected in this way the generator load decreases slightly with the external load. This would put too great a load on the battery at the time of maximum discharge.

As a concrete example illustrating the application of the foregoing analysis assume

E_M = 550 volts.
h = 0.15.
I_0 = 100 amperes normal.
I_x = 400 amperes maximum.
R = 0.14 ohm.
k = .02 volt.
E_A = 525 volts.
$V = E_M - E_A - I_0h = 10$ volts.
$T = \frac{0.14}{.02} = 7$ turns.
$N = \frac{525}{2.1} = 250$ cells.

Shunt coil connected across the line.

With any given values of E_A, R and V, I_0 will remain unchanged whatever may be the variation of I_x.

If E_A varies and V be not varied to compensate therefor, I_0 will vary, but will be independent of the external load.

When $E_A + V = E_M$, I_0 reduces to zero and the battery carries the total external load.

When E_A is a minimum, I_0 is greatest if V remains constant.

If the battery is discharged to 1.65 volts per cell and has a floating voltage of 2.1, the value of R for minimum battery voltage and maximum discharge is

$$R = \frac{(2.1 - 1.65)\,N}{I_{x\,max} - I_0} = \frac{0.45 \times 250}{300} = 0.425.$$

Greatest value of I_0 is therefore (equation 72)

$$I_0 = \frac{550 - 10 - 525 + 400\,(0.425 - 0.14)}{0.425 + 0.15 - 0.14}$$

$$= 296.55 \text{ amperes.}$$

Of course this is an abnormal current that might occur under extraordinary conditions, but E_A would seldom fall to 1.65 volts per cell without manipulation of the rheostat, which would leave the system in an approximately proper condition to make the battery take its share of the load.

Shunt coil connected across the battery.

The calculations for I_0 when the shunt coil is connected across the battery may be made by substituting in equation (77).

For normal battery charge and $R = 0.14$, with $I_x = 400$

$$I_0 = \frac{550 - 525 - \frac{10 \times 525}{550} + 400\left(\frac{10 \times 0.14}{550}\right)}{0.15 + \frac{10 \times 0.14}{550}}$$

$$= 108 \text{ amperes.}$$

Under same conditions with shunt coil connected across the line $I_0 = 100$ amperes (equation 73), showing that the regulation is better if the shunt coil be connected across the line.

When E_A rises, and V is not reversed, the battery tends to take all the external load. Therefore, conditions may occur under which I_0 will fall as low as 50 amperes, while $I_x = 400$. The carrying capacity of the booster armature and series coil should be 350 amperes for, say, 3 minutes.

The maximum voltage that the shunt coil must produce is that required to overcharge the battery, and for 2.7 volts per cell is equal to

$$2.7 \times 250 - 550 = 125 \text{ volts.}$$

Since, at times, the current flow through the booster may be 350 amperes, the capacity of the booster is $125 \times 350 = 43.75$ K.W. As the heavy current outputs last only a minute or two, 40 per cent of this, or 17.5 K.W., is large enough.

The maximum booster output is when sending maximum current from the battery at the time of battery exhaustion.

Booster volts $= 550 - 100 \times 0.15 - 250 \times 1.65 = 122.5$ volts.

Current $= 300$ amperes.

Output $= 300 \times 122.5 = 36.75$ K.W.

Taking 40 per cent of this, the size of the motor is 14.7 K.W.

All the foregoing computations are subject to correction for motor current which makes the battery current greater than $I_x - I_0$, as set forth in Chapter XXXV.

From Fig. 178 it may be seen that the load may be connected to the line, either between the booster and the power station or between the booster and extreme end of the line. The battery and booster may therefore be located on a railway feeder at the point of greatest drop. The battery may also be made to help the power station on the peak of the load by manipulating the rheostat as E_A falls.

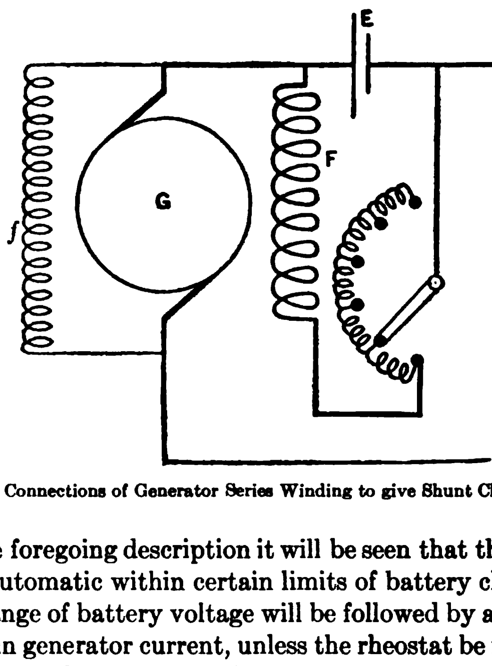


FIG. 179. Connections of Generator Series Winding to give Shunt Characteristic.

From the foregoing description it will be seen that the compound booster is automatic within certain limits of battery charge. Any marked change of battery voltage will be followed by a corresponding change in generator current, unless the rheostat be manipulated to bring $E_A + V$ back to normal.

While the theoretical generator current variation is small for a given change of load, there is always a sudden, momentary current rush from the generator on increase of load, the duration of which is equal to the time lag of magnetization of the booster field. Lights on a circuit with variable load will "wink" on sudden changes of load. In this respect the compound booster is not so satisfactory as the "constant-current" booster, as in the latter *all*

generator current passes through the series fields, which, by reason of their self-induction, oppose and check any sudden current rush, giving the booster field time to change its magnetization to the proper degree.

This system, depending as it does on the rise and fall of generator voltage with corresponding change of load, requires that the generator be a shunt machine or its equivalent.

Where a plant has in operation a generating equipment of compound-wound dynamos, and this booster and battery system is installed, some change must be made in the generators. If the series field be entirely cut out, the dynamo will not generate the normal pressure at normal load. In order to make use of the existing machines and windings, the arrangement shown in Fig. 179 is resorted to.

In this diagram G is the generator, f and F its shunt and series fields, respectively, E a low-voltage accumulator — usually one or two cells — and R a variable resistance in series with the series field circuit. The battery is connected in multiple with the series coil and resistance R, as shown. When the load on the generator is normal, the drop through $F + R$ is equal to the battery voltage. If the generator load rises, $(F + R)\ I_0$ is greater than the battery voltage, and the current divides, part going through the battery and the normal current going through $F + R$. Should the load decrease and battery voltage be greater than $(F + R)\ I_0$, the battery discharges and sends the normal current through $F + R$. The variation in I_0 will be small, owing to the regulating effect of the main battery and booster on the line.

Since, with this arrangement, the generator excitation is the sum of a constant excitation and an excitation that varies inversely as the load, its characteristic will be similar to that of a shunt machine.

The Differential Booster.

This booster is used on power and railway circuits where the load fluctuates widely and suddenly. There are several varieties of this type of booster, and many patents have been issued covering the different methods of varying the voltage of the machine.

One of the earliest automatic boosters was that of Mailloux.* This system is shown diagrammatically in Fig. 180.

The original arrangement is that of a battery E in series with a

* Amer. Pat. No. 430868, June 14, 1890.

booster armature B. This combination is connected across the mains L, L′, the generator G being the source of supply. The total current supplied to the line passes through the series field, S, on the booster. It is evident that within the limits of saturation the voltage of the booster will vary directly as the external load. This voltage is opposed to that of the generator and tends to discharge the battery. When the load is light the booster voltage is low, and the generator potential overcomes both it and the battery voltage and sends a charging current into the battery.

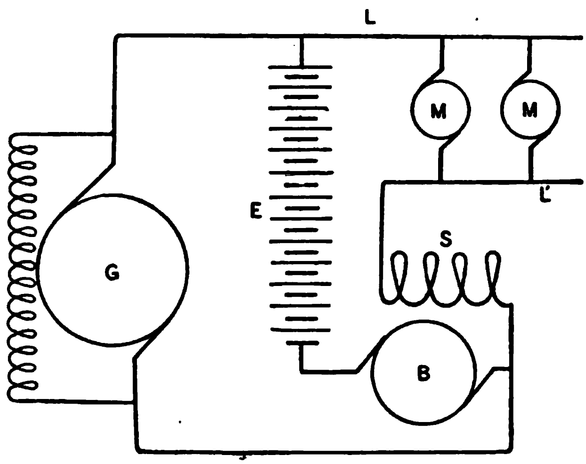


FIG. 180. Connections of Load Controlled Booster.

At normal load the series field produces an electro-motive force, which, added to that of the battery, balances the generator electromotive force and current flows neither into nor out of the battery. A load greater than normal raises the booster voltage, causing it to discharge the battery at a rate proportional to the external load.

The differential booster in one of its forms is as shown in Fig. 181. In this the shunt coil *f* opposes the series coil S, tending to produce pressure in the same direction as the generator pressure, and to send current into the battery. At normal load the series and shunt coils balance each other, the voltage of the booster is zero, and current flows neither into nor out of the battery. A heavy load causes the series to overpower the shunt field, and the voltage of the booster is in such a direction as to discharge the battery. A load lighter than normal allows the shunt to overpower the series field, and the

booster pressure is added to the generator voltage, causing a charging current to flow into the battery.

The differential booster commonly used is a modification of that of Mailloux, and designed by J. B. Entz.* This system is explained by Fig. 182.

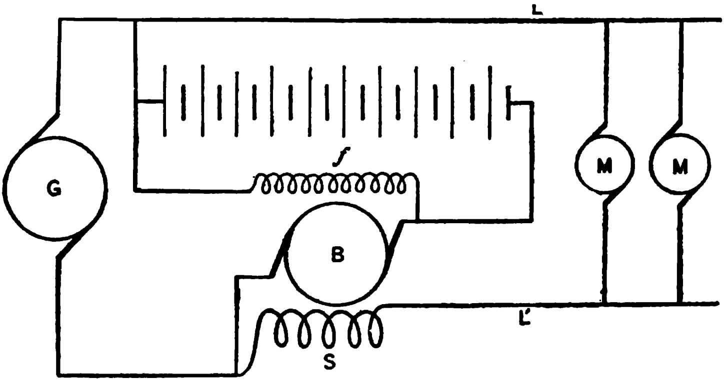


Fig. 181. Connections of Simple Differential Booster.

G is the generator, B the booster armature, E a battery, f the shunt field of the booster connected across the line, S_1 and S_2 series fields, L, L′ the mains and M, M the external load.

As shown, S_1 is in series with the generator and carries all current supplied. S_2 carries all current supplied to the external circuit, which, at any time, is equal to the algebraic sum of the generator

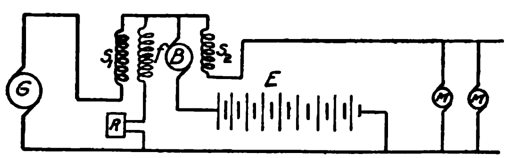


Fig. 182. Connections of Differential Booster.

and battery currents, when the generator and discharge currents are taken as positive and charging current as negative.

S_1 and S_2 act together to produce an excitation opposed to that produced by the shunt field. As the object of this system is to maintain a constant load on the generator, S_1 may be considered as constant. The field then due to $f - S_1$ is constant. If at normal load $(f - S_1) - S_2 = 0$, the booster voltage will be zero, and there

* Amer. Pat. No. 625098, May 16, 1899.

is neither charge nor discharge. As S_2 varies directly with the external load, an increase or decrease will result in a booster e.m.f. acting to discharge or to charge the battery. This action is, in fact, the same as that of Mailloux's differential booster, considering $(f - S_1)$ as the equivalent of the opposing shunt field of Mailloux's system.

The reason for the application of S_1 lies in the fact that any considerable variation in the battery voltage will disturb the equilibrium of the system unless this compensating coil is used. If the voltage of the battery be lower than normal, it will not discharge rapidly enough to relieve the generator of overload fluctuations unless the booster pressure be increased, and the generator will therefore have to supply a current greater than its normal capacity. If, however, a current greater than normal flows through the coil S_1, the value of $(f - S_1)$ is reduced, and S_2 still further overpowers the resultant of those two and causes a higher booster pressure, tending to discharge the battery, and thus bringing down the generator load to normal. Should the battery voltage be above that it ordinarily has, the reverse operation will take place; the battery tending to discharge too rapidly will have its discharge rate reduced and the generator allowed to take its share of the load, because of the booster voltage being lowered by decreased current in S_1, due to light load on the generator.

This system is entirely automatic with the exception of occasional variations in the strength of shunt field f, effected by means of rheostat R, to compensate for changes in the battery pressure. It is adapted for systems supplying both light and power, where the lighting mains are connected to L and L_1 between the booster and the generator, this portion of the load being non-fluctuating.

The fluctuating load must be connected to the mains *after* they pass through their proper booster connections.

In the compound booster system, it will be remembered, power can be taken from either side of the booster connections.

As in the case of the compound booster, the battery may be made to help the generator carry the peak of the load as well as take up the fluctuations. This booster will operate satisfactorily with a compound-wound generator as the source of supply. For calculating the size and windings of this booster the following analytical discussion is necessary:

At normal load and normal battery voltage there should be

neither charge nor discharge, and the booster voltage should be zero. Let the maximum voltage of battery, on regulation, equal 2.4 N, N being the number of cells in series. The normal voltage equals ϵN, ϵ being the open circuit or floating voltage per cell.

Let

E_M = generator voltage at no load.
E_A = battery voltage on open circuit.
V = booster volts due to shunt coil only.
I_0 = generator current.
I_x = current in external load.
R = battery circuit resistance, including booster armature, for normal condition of battery charge.
t_1 = number of turns in coil S_1.
t_2 = number of turns in coil S_2.
k = volts produced per ampere turn on booster field.
h = volts drop in generator voltage per ampere of generator current.

If I_0 be first assumed as equal to the average generator current, then $E_M - I_0h$ = normal voltage at booster and battery terminals $= E_0$. If the generator is compounded to give a constant e.m.f., $h = 0$. If it be overcompounded h is negative and $E_0 = E_M + I_0h$.

The equations of the three conditions under which the booster must work, neglecting current required for the driving motor, are:

For battery normally charged, the booster voltage must be zero when $I_x = I_0$. The equation is

$$E_0 + V = E_A + I_0k(t_1 + t_2). \qquad (81)$$

If the battery is nearly up to full charge so that the increase in voltage with charging current is considerable, and if the regulation is to be ϕ per cent, the condition for zero external load and $100 - \phi$ per cent generator load, is

$$E_0 + V = E_{A\,MAX} + \frac{100 - \phi}{100} I_0kt_1. \qquad (82)$$

When the battery charge is nearly exhausted, and the voltage falls to say 1.65 volts per cell on full discharge the conditions are

$$E_0 + V = E_{A\,MIN} + \frac{100 + \phi}{100} I_0kt_1 + I_xkt_2. \qquad (83)$$

These three equations show that the conditions cannot be fulfilled if V is constant. The excitation due to the shunt coil must,

therefore, be varied manually, by means of a rheostat, with change in condition of battery charge.

The minimum value of V is as given in equation 83 and is

$$V = E_{A\,MIN} - E_0 + \frac{100 + \phi}{100} I_0 k t_1 + I_x t_2 k. \qquad (84)$$

The maximum value is under the conditions given in equation 82 and is

$$V = E_{A\,MAX} - E_0 + \frac{100 - \phi}{100} I_0 t_1 k. \qquad (85)$$

For normal regulating conditions, which is the basis on which the series turns are computed,

$$V = I_0 k (t_1 + t_2) \qquad (86)$$

the factors E_A and E_0 disappearing, as they are equal for this condition.

When the booster is used only for charging the battery, the shunt coil alone is used, the two series windings being short-circuited. On overcharge, the battery voltage will exceed the generator pressure by an amount equal to 0.6 N, if the floating voltage of the battery equals the generator pressure; V therefore must be not less than 0.6 N.

Also, from equation 86, the maximum value of V on regulation is

$$V = 0.3\,N + \frac{100 - \phi}{100} I_0 t_1 k. \qquad (87)$$

In this equation 0.3 N is based on the assumption that on regulation the battery voltage will not rise more than 0.3 volt per cell above the normal floating voltage.

In order to compute the series windings some value of V must be adopted. This value is usually fixed to accord with the maximum as given by equation 85.

From equation 86, for the booster voltage to be zero when $I_x = I_0$

$$I_0 (t_1 + t_2)\, k = V, \therefore t_1 + t_2 = \frac{V}{I_0 k}. \qquad (87)$$

As the load increases, the voltage produced by the series coils must exceed V by an amount equal to the drop due to resistance of battery circuit, or

$$k (I_0 t_1 + I_x t_2) = V + R (I_x - I_0), \qquad (88)$$

the current supplied by the battery being $I_x - I_0$. As I_0 is to

remain constant as long as the condition of battery charge remains normal, the increase of series excitation must be supplied by coil S_2. Then

$$kt_2(I_x - I_0) = R(I_x - I_0), \quad \text{or} \quad t_2 = \frac{R}{k}. \tag{89}$$

From these equations, the windings of the three coils are determined. In using the factor k, a constant permeability and straight line characteristic are assumed. This is sufficiently true for practical purposes. Remembering that the shunt coil voltage varies with variation in E_A, if f be connected across the battery terminals, V becomes

$$\frac{VE_A - VRI_x + VRI_0}{E_0}. \tag{90}$$

If the shunt winding be connected across the line, the equation of electro-motive forces with normal condition of battery charge is

$$I_0t_1k + I_xt_2k - V - E_0 + E_A + RI_0 - RI_x = 0. \tag{91}$$

But for normal condition of battery, $t_2k = R$. Therefore,

$$I_0 = \frac{V + E_0 - E_A}{t_1k + R}. \tag{92}$$

This shows that I_0 is constant for any value of E_A that changes only within the limits of drop or increase due to R. If the shunt coil be connected across the battery the equation becomes

$$I_0t_1k + I_xt_2k - \frac{VE_A}{E_0} - I_x\frac{VR}{E_0} + \frac{VRI_0}{E_0} - E_0 + E_A + RI_0 - RI_x = 0. \tag{93}$$

Whence
$$I_0 = \frac{E_0 + \frac{VE_A}{E_0} - E_A + I_x\frac{VR}{E_0}}{t_1k + R + \frac{VR}{E_0}}. \tag{94}$$

With a given value of E_A, all the terms of this equation are constant, except I_x showing that I_0 varies with I_x. The factor $\frac{VR}{E_N}$ is, however, small.

It must be remembered that the value of R for the condition of battery exhaustion becomes $R = \frac{(\epsilon - 1.65)N}{I_{x\,MAX} - I_0}$, ϵ being the floating voltage per cell. This value must always be used when solving for I_0 when battery is exhausted.

Consider now the concrete case of a railway circuit having the following characteristics:

$E_0 = 500$ volts.
$E = 2.1$ volts = floating voltage per cell.
$N = \frac{500}{2.1} = 238$ cells.
$E_A = 500$ volts.
$I_0 = 100$ amperes average.
$I_x = 400$ amperes maximum.
$R = 0.16$ ohm.
$k = .02$ volts per ampere turn.
$h = 0. \quad \therefore E_M = E_0.$

Computations based on normal battery charge.

The first quantity to be determined is V. V for charging = $0.6 \times 238 = 163$ volts.

From equation 89,

$$t_2 = \frac{0.16}{.02} = 8.$$

t_1 should never exceed such a value that would require that V be greater than 0.6 N. Otherwise the booster would be abnormally large.

From equation 87, which gives the maximum value of V on regulation,

$$V = 0.3 \times 238 + (0.94 \times 100 \times .02 \times t_1).$$

Putting $$V_{MAX} = 0.6\ N = 163,$$
then $$t_1 = 48+ \text{ turns}.$$

Experience has shown that a fewer number of turns than this maximum number may be used. About 75 per cent of the maximum is good practice.

Calling this 36 turns, so that on regulation the booster will work on the straight portion of the magnetization curve, then for normal battery charge

$$V = 100\ (36 + 8) \times .02 = 92 \text{ volts}.$$

For minimum value of battery voltage, $\epsilon = 1.65$ volts per cell, when $I_x = 400$ amperes the battery pressure is 393 volts. If the per cent regulation is to be 6, i.e., $\phi = .06$, then for this condition (equation 84)

$$V = 393 - 500 + (1.06 \times 100 \times .02 \times 36) + (400 \times .02 \times 8).$$

Whence $$V = 33.3 \text{ volts}.$$

For regulation with a fully charged battery and same value of ϕ and $\epsilon = 2.3$; from equation 87

$$V = 71.4 + (0.94 \times 100 \times 36 \times .02) = 140 \text{ volts.}$$

The rheostat, therefore, must be designed to vary the voltage due to the shunt coil from 33 volts up to the maximum of 163 volts.

If the rheostat be left unattended and so set that the normal, regulating, shunt-coil voltage is 92 volts, the current from the generator for battery fully charged and no current to the line is (equation 85)

$$I_0 = \frac{92 + 500 - 571.2}{36 \times .02} = 28.75 \text{ amperes.}$$

For minimum battery voltage and $I_x = 400$ amperes.

From equation 84

$$I_0 = \frac{V + E_0 - E_A - I_x t_2 k}{t_1 k}. \tag{95}$$

Substituting the proper values,

$$I_0 = \frac{92 + 500 - 393 - (400 \times .02 \times 8)}{36 \times .02} = 187.5 \text{ amperes.}$$

The maximum battery output at any time will be $I_x - I_0$ amperes. If the battery voltage should rise, I_0 will fall to 28.75 amperes. $400 - 28.75 = 371.25$ amperes, which is the maximum current through the armature. Taking the arbitrary figure of 40 per cent of this, because of the momentary character of the load, the size of the machine should be for 148.5 amperes continuous output and to produce a pressure of 163 volts, which is 24.2 K.W.

The maximum output is when the maximum battery discharge takes place and the battery is nearly exhausted.

Amperes $= 400 - (100 - 6) = 306$.

Volts $= 500 - 393 = 107$.

Output $= 32.75$ K.W.

Taking 40 per cent of this figure gives the size of the driving motor, which is 13.1 K.W.

If the shunt coil be connected across the battery terminals the regulation will be much better for a constant setting of the rheostat and varying condition of battery charge than if it be connected across the line. For a practically constant condition of battery charge, the regulation is better with the shunt coil connected across the line. Therefore the shunt winding should be connected across

the line or across the battery according to the conditions under which the installation is to work.

All the foregoing equations and computations are subject to correction for the true value of the battery charge or discharge, which is less or greater than $(I_x - I_0)$ by the amount of current required to drive the booster motor and as set forth in Chapter XXXV.

Constant Current Booster.

The regulating boosters before described — the compound and the differential — are also called "reversible boosters," because the direction of current flow through the armature changes with charge or discharge. They are adapted to systems where the lines are long and the line drop is high, as they maintain the line voltage constant at the point of their connection to the circuit, whatever the external load may be.

In systems where the lines are short and the drop small, it is often desirable to have the voltage fall on application of overload. The reason of this is that the overload is produced by the current rush due to starting of motors, and if the pressure be lowered, the motors start more easily and the accelerating current is decreased.

This condition prevails in buildings where elevator, printing press and other motors are used, which frequently start and stop. For such systems the constant-current booster is best adapted, and it is sometimes used on railway and other circuits of a like nature, being installed instead of the compound or differential. This booster is also called the "non-reversible" booster, as current flows through it in one direction only, regardless of load changes or whether the battery be charged or discharged.

The Entz * constant-current booster is shown diagrammatically in Fig. 183.

In the diagram, G is the generator, B the booster armature, E battery, S series coil, *f* shunt coil, S_1 switch short-circuiting series coil, R rheostat, ×, ×, ×, × non-fluctuating load requiring constant potential, M, M fluctuating load, and L, L_1 the mains.

It is to be noted that all current used by the fluctuating load or delivered to the battery, must pass through the series coil and armature, and that there is never a reversal of current in the booster; also that the voltage impressed on the fluctuating load is greater than that on the non-fluctuating load by an amount equal to the booster voltage

* Amer. Pat. No. 625100, May 16, 1899.

The shunt coil creates a pressure in the same direction as that of the generator. The series coil opposes the shunt coil, and therefore produces a pressure opposing that of the generator.

When a load comes on the power circuit, the generator tends to send additional current through the booster to meet this demand. The action of increased current is, however, to cut down the voltage of the booster in a direct proportion to the increase in excitation from the series field, causing the sum of the generator and booster voltages to diminish with increase of load on the power circuit, thus causing, under any condition — up to full battery

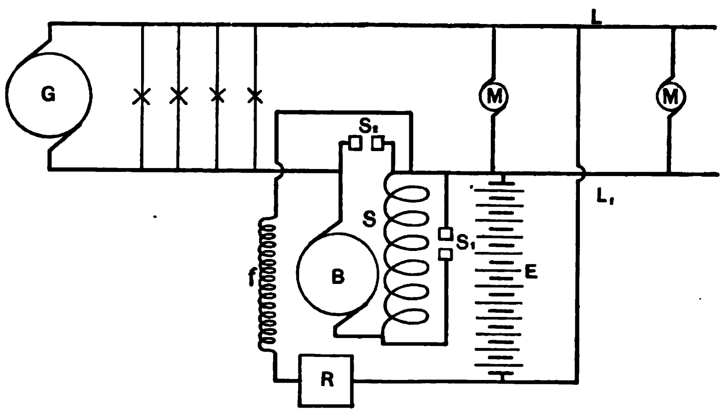


FIG. 183. Ents "Constant Current" Booster.

charge — a substantially constant-current delivery from the generator regardless of the load fluctuations on the external circuit.

On systems where the battery serves for regulation only, the booster carries only the *average* current and not the maximum of the fluctuations, as do the series, compound and differential boosters. The machine and its driving motor may therefore, under certain conditions, be considerably smaller than a compound or differential booster to give the same service.

Following is an analytical discussion of the constant-current booster:

Let

E_M = generator voltage at no load.
E_0 = normal line voltage on generator side of booster.
E_A = normal battery voltage.
E_B = booster voltage.

V = voltage due to shunt coil at normal battery voltage.
I = number of turns in series field.
I_0 = generator current to power.
I_x = current in external load.
R = resistance of battery circuit.*
r = resistance of booster armature and series field.
k = volts produced per ampere turn on booster field.
N = number of cells in series.
h = volts drop at generator per ampere of generator current.

The minimum battery voltage should be the same as the generator voltage, as it is often desirable to connect the battery on to the generator circuit by closing S_2, and supply the lighting current for short periods during which the generator is shut down and disconnected from the circuit.

Therefore, $N = \frac{E_0}{1.7}$.

The battery is installed with some of the cells on one end connected to points on an end cell switch, and so arranged that when connected on the lighting load and discharging, these cells can be cut in as the voltage drops. This arrangement will be explained later.

The maximum voltage of battery on regulation, and consequently the maximum voltage across the power bus bars, is 2.4 N. The average voltage will be $2.1 \times N$. The voltage due to the shunt coil will, for purposes of calculation, be assumed as equal to the difference between the generator voltage and the maximum battery voltage, or $2.4\,N - E_0$.

When the outside load is normal and the battery is at normal voltage, the booster voltage $= E_A + rI_0 - E_0$, (96)
and current flows neither into nor out of the battery. Therefore,

$$V - TI_0k = E_A - E_0 + rI_0, \tag{97}$$

whence

$$T = \frac{V - E_A + E_0 - rI_0}{I_0k}. \tag{98}$$

This assumes a constant permeability. Knowing V, E_A, E_0, k, r and also the average load, or I_0, T is determined. Remembering that the excitation of the shunt coil will vary directly as the volt-

* Virtual resistance.

age of the battery to which it is connected, the booster voltage due to the shunt coil for any battery voltage will be

$$V^1 = \frac{VE_A - VRI_x + VRI_0}{E_A}. \tag{99}$$

For any external load or battery voltage, the following is the equation of electro-motive forces:

$$\frac{VE_A - VRI_x + VRI_0}{E_A} - I_0Tk - I_0r - I_0h + E_0 - E_A = R(I_0 - I_x) \tag{100}$$

whence

$$I_0 = \frac{E_0 + V + RI_x\left(1 - \frac{V}{E_A}\right) - E_A}{Tk + r + h + R\left(1 - \frac{V}{E_A}\right)}. \tag{101}$$

Since for any given condition of battery, all the factors in equation (101) are constant except I_x, the generator load varies with the external load. It is evident that the higher V is made the better the regulation will be.

If the shunt coil be connected across the bus bars on the generator side, V will be a constant and equation (100) will become

$$V - I_0h - I_0Tk - I_0r + E_0 - E_A = RI_0 - RI_x \tag{102}$$

and

$$I_0 = \frac{E_0 + V - E_A + I_xR}{Tk + r + R + h}. \tag{103}$$

Comparing this equation with equation 101, it is clear that the regulation is better with the shunt coil connected across the battery terminals.

The following example will illustrate the methods of calculation:

Assume a 125-volt, two-wire system furnishing current to lights and electric elevators. Assume

$$I_0 \text{ average} = 50 \text{ amperes.}$$
$$I_x \text{ maximum} = 300 \text{ amperes.}$$
$$r = .2 \text{ ohm.}$$
$$R = .2 \text{ ohm.}$$
$$k = .02.$$
$$E_0 = 125 \text{ volts.}$$
$$h = 0.$$
$$N = \frac{125}{1.7} = 73.5, \text{ say } 73.$$

By means of the end cell switch, the number of cells across the bus bars may be varied and the number usually put in circuit is such as to give a minimum voltage of 1.85 per cell and a total voltage at least 4 volts above that of the generator. For this case

$$N = \frac{125 + 4}{1.85} = 69.7, \text{ say } 70.$$

$E_A = N \times 2.1 = 147$ volts = average voltage across power mains.

$E_{A\,MAX} = 2.4 \times 70 = 168$ volts.

$E_{A\,MIN} = 70 \times 1.85 = 129$ volts.

Range of voltage through which motors operate = 168 − 129 = 39 volts.

Assume V = 100 volts. Then from equation 98,

$$T = \frac{100 + 125 - 147 - 0.2 \times 50}{50 \times .02} = 68 \text{ turns.}$$

Assume $I_x = 0$. Then from equation 101,

$$I_0 = \frac{100 + 125 - 147}{68 \times .02 + 0.2 + 0.2 - \left(1 - \frac{100}{147}\right)} = 48 \text{ amperes.}$$

If $I_x = 50$ amperes,

$$I_0 = \frac{78 + 0.2 \times 50\left(1 - \frac{100}{147}\right)}{1.624} = 50 \text{ amperes; and,}$$

for $I_x = 300$, $I_0 = 59.8$ amperes.

The minimum generator current will be when the battery is at its maximum voltage, and $I_x = 0$.

Then $$I_0 = \frac{100 + 125 - 168}{1.624} = 35.2 \text{ amperes.}$$

I_0 is a maximum when E_A is a minimum, and $I_x = 300$.

Then $$I_0 = \frac{100 + 125 - 129 + 300\ (.064)}{1.624} = 70.7 \text{ amperes.}$$

Proper attention to the rheostat will prevent I_0 from ever rising so high.

If V were 50 volts, T would be 18 turns, I_0 would be 40.4 amperes for $I_x = 0$, and 99.3 amperes for $I_x = 300$ amperes with E_A normal. With $E_A = 126$ volts and $I_x = 300$, I_0 would be 125 amperes.

V then is determined by the regulation desired. The greater V is, the better the regulation, but the size of the machine increases with increase of V.

While the generator current varies with any variation of E_A'', the latter changes gradually, and does not cause any sudden fluctuation of generator load. If the battery is used only for regulation, its voltage will vary but little; but if used to carry light loads or help the generator carry the peak of the load, E_A may vary from 2.5 N down to 1.8 N, and rheostatic control is necessary.

V must always be great enough to give the battery an overcharge when the series coil is short-circuited. In the case just considered, the maximum voltage of the battery with all cells in circuit will be

$$73 \times 2.7 = 197.1 \text{ volts.}$$

Deducting the generator pressure, 126 volts, the booster voltage due to the shunt coil is found to be 71.1 volts.

For good regulation, however, the pressure due to the shunt winding should be greater than this, as has been shown.

The size of motor required is fixed by the product of booster volts multiplied by amperes taken at the same instant and when their product is a maximum.

This maximum occurs when the series field is short-circuited by closing S_1 (see Fig. 183), and a charging current is being sent into the battery, and E_A is maximum. If this current = 50 amperes, and the booster voltage = 71.1 volts, as before computed, the size of the motor is $\frac{71.1 \times 50}{0.80} = 4.4$ K.W., 0.80 being assumed as the booster efficiency at full load.

All the equations and computations dependent on the value of the current to or from the battery must be corrected to include current for the driving motor as given in Chapter XXXV.

It is to be noted that in non-reversible boosters a heavy current flow may take place at times when the booster voltage is low. Sparking will result unless the air gap be large, or a compensated winding which neutralizes armature reaction, be used. Interpole machines also work successfully under these conditions. Since the voltage of the booster decreases for battery discharge, and the current flow increases only slightly, the motor load decreases with battery discharge. Hence the correction in the foregoing formulæ and computations for motor current will appear as a negative quantity, as explained in Chapter XXXV.

In computing the size of a booster of this type it must be remembered that the current through it does not fluctuate from zero to a maximum, but is substantially constant, and its actual capacity must be nearly the maximum value calculated. In the case just discussed, with V = 100, when $I_x = 300$, I_0 maximum is 70.7

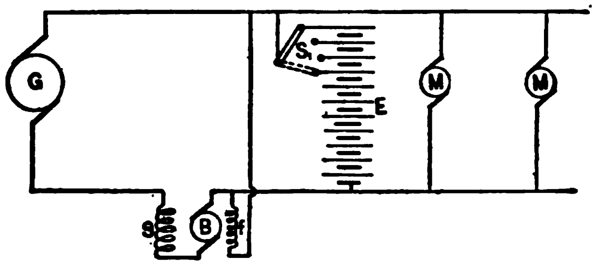


FIG. 184. Connections, Constant Current Booster with End Cells.

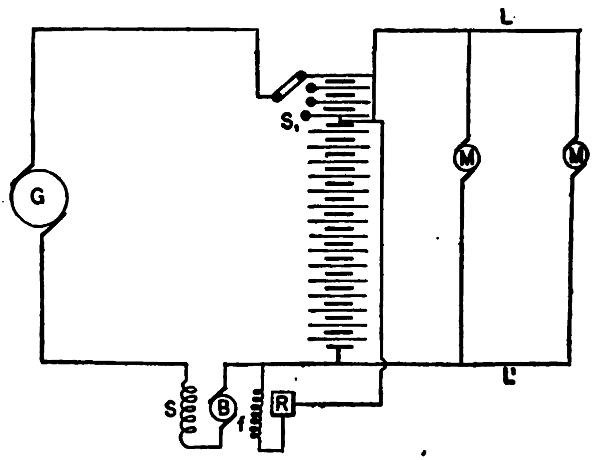


FIG. 185. Connections, Constant Current Booster with End Cells.

amperes, and the conditions under which this current is delivered might continue for several hours. The current through the booster therefore would fluctuate between 50 and 70.7 amperes. If it were designed for 50 amperes continuous output, the higher current value would appear as a momentary 40 per cent overload, which is within the limits of good practice. The size of the booster then would be 50 × 100 = 5 K.W. The frame, however, would have to be larger than that indicated by this computation in order

to accommodate the series windings which would comprise 68 turns having a total resistance of less than 0.2 ohm.

The end cell arrangement before mentioned may be as indicated in Fig. 184 or Fig. 185. In Fig. 184 the circuit is from L through all the cells out to L′, when the end cell switch S_1 is thrown on the last point, as shown by the full line. When the generator is cut out and the battery used as the source of supply, the end cell switch is thrown on such a point as will place in series between the mains the proper number of cells to give the normal voltage of the *generator side* of the system.

With this arrangement it is evident that the voltage fluctuation on the power side of the system equals 1.85 N to 2.4 N, N being the number of cells put into circuit by the end cell switch.

Another arrangement is shown in Fig. 185. In this, the battery, exclusive of end cells, is connected across the power bus bars. The end cells connect to the generator bus bars through the end cell switch S. This latter arrangement is not so good as the one shown in Fig. 184, as the number of cells across the power circuit cannot be varied to compensate for change in condition of battery charge.

CHAPTER XXXIII.

SEPARATELY EXCITED BOOSTERS.

THE self-excited or multiple-wound boosters, described in the previous chapter, while in general use, are not now made, as the separately excited or externally controlled types have been found better in points of good regulation, low cost and high efficiency.

One of the separately excited kind is that of Hubbard,* which is as shown in Fig. 186. This booster is known as the "Counter

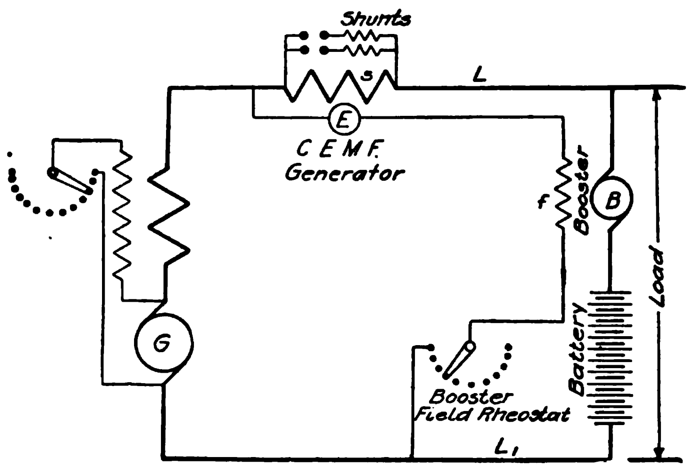


FIG. 186. Counter E.M.F. Booster.

E.M.F." booster. G is the supply generator, B the booster armature connected in series with the battery, the two being connected across the mains, L and L′. E is the armature of a small exciting generator connected in series with the field, *f*, of the booster, the circuit of exciter armature and field winding being also connected across the mains L, L′. A rheostat is included in the circuit.

S is the field winding of the exciting generator, and carries the

* Amer. Pat. 651664, June 12, 1900.

generator current or a portion thereof, the proportion being regulated by means of the adjustable shunt, which is in parallel with S.

The voltage of the booster is in opposition to, or in the same direction as, that of the generator, according to whether the pressure of E is greater or less than that of the line. The pressure of the exciting generator opposes the current flow from the line through field *f* of booster. The voltage of the exciting generator varies with the change in generator output, thus causing the booster pressure to vary with the external load.

At normal load the battery and generator pressures balance and there is no battery charge or discharge. The voltage of E being equal and opposite to the line voltage, no current flows either way through *f* and the booster gives no electro-motive force in either direction.

If the load should increase, the current from the generator will also tend to increase, thus raising the voltage of E so that it will exceed that of the line, and current will flow through *f* in such a direction as to cause discharge. A decrease of load will result in a lower voltage at E and the line voltage being the greater, will pass current through *f* in such a direction as to cause charge, the booster pressure being added to that of the generator.

On discharge, the battery output is proportional to the excess of generator load above normal up to the limit of saturation of the field magnets of E. This system was designed with a view to limiting the discharge of the battery, and in case of the load exceeding the normal generator plus maximum battery output, to stop the booster voltage from rising proportional to the load increase, and so make the generator work at an overload and assist the battery, thus in a measure protecting it from injurious discharge rates.

The analytical discussion of this system is as follows:—

Let E_0 = voltage of generator on open circuit.

h = change in generator voltage per ampere of output. h is positive for an increase in pressure with load (compounded generator) and negative for a decrease in voltage (shunt generator).

E_A = normal battery voltage on open circuit.

I_0 = amperes normal generator output.

I_x = amperes to external load.

R = virtual resistance of battery and booster circuit with normal battery charge.

k = volts generated in exciter armature per ampere turn on the field.

T = number of turns in the exciter field coil.

Q = volts generated in the booster armature per volt applied to its field winding.

E = volts per cell of battery.

From the conditions, the booster voltage must be zero when $E_A = E_0 + I_0h$ and $I_x = I_0$.

When the booster voltage is zero, the exciter voltage is just equal to the generator pressure or

$$E_0 + I_0h = I_0Tk; \tag{104}$$

whence

$$T = \frac{E_0 + I_0h}{I_0k}. \tag{105}$$

Also, when the external load differs from that of the generator and the value of I_0Tk changes, the difference between the generator pressure and that of the exciter fixes the voltage impressed on the booster field, and since for each volt impressed on the booster field, Q volts are generated in the booster armature,

$$\text{Booster volts} = (E_0 + I_0h - I_0Tk)\,Q,$$

which is also equal to the change in battery pressure; hence

$$(E_0 - I_0\,(Tk - h))\,Q = -\,R(I^x - I_0). \tag{106}$$

The negative sign in front of the right-hand member of the equation signifies that for increase of I_x, battery discharge takes place, producing a diminution in battery voltage. Q is fixed by the regulation required. If I_0 maximum is not to be greater than ϕ per cent above the normal value of I_0 when I_x is maximum, the equation is

$$Q = \frac{-R\,(I_{x\,MAX} - I_0\,(1 + \phi))}{E_0 - I_0\,(1 + \phi)(Tk - h)}. \tag{107}$$

Also, if I_0 minimum is to be not less than ϕ per cent below the normal value of I_0 when I_x is zero and the battery is at or near full charge, then

$$(E_0 + I_0\,(1 - \phi)\,h - I_0\,(1 - \phi)Tk)\,Q = RI_0\,(1 - \phi); \tag{108}$$

whence

$$Q = \frac{RI_0(1 - \phi)}{E_0 - I_0\,(1 - \phi)(Tk - h)}. \tag{109}$$

Q is computed from both formulæ and the larger value taken. Except under unusual conditions, the larger value will be given by equation 107.

From equation 106

$$I_0 = \frac{QE_0 + RI_x}{Q(Tk - h) + R}. \tag{110}$$

R must be computed for the condition of battery charge that is assumed to exist, when making calculations. The maxima on discharge and charge are used in formulæ 107 and 109 to compute Q.

As a practical illustration consider a system as follows:

Generator compound wound for 10 per cent increase in voltage at full load above open circuit voltage, which latter is 500 volts.

Normal generator voltage 550 volts.

Normal generator current 300 amperes.

Maximum load current 750 amperes.

Then $E_0 = 500$.

$I_0 = 300$.

$h = 50$ volts for 300 amperes $= 0.166$.

$E_A = 550$ volts on open circuit.

$E = 2.10$ volts on open circuit.

$N = 262$ cells.

$I_x = 0$ to 750 amperes.

$R = .08$, normal.

$k = .02$.

$\phi =$ per cent regulation $= .05$.

From equation 105

$$T = \frac{500 + 50}{300 \times .02} = 91.6, \text{ say 92 turns.}$$

To determine Q, the maximum value of R for any condition of battery charge must be found.

If the battery voltage falls to 1.65 volts per cell when the charge is nearly exhausted and when discharging $750 - 300\,(1.00 + .05) = 435$ amperes, the drop will be $(2.10 - 1.65)\,N = 0.45 \times 262 = 118$ volts. For this case, therefore, $R = \frac{118}{435} = 0.271$. This value is to be substituted in equation 107.

For an increase up to 2.4 volts per cell when the battery is charged, the rise is $(2.4 - 2.1)\,N = 0.3 \times 262 = 78.6$ volts. This

rise will take place when $I_x = 0$ and $I_0 (1 - .05) = 300 \times .95 = 285$ amperes is being sent into the battery.

$$\text{In this case, } R = \frac{78.6}{285} = 0.276.$$

This value is to be substituted in equation 109.

If the limits of voltage through which the battery is desired to work be increased or decreased above or below those here assumed, R_{MAX} will likewise be correspondingly changed, and must be computed as above. The limits here taken represent good practice and need not be exceeded except under extraordinary conditions.

Substituting values of R, equation 107 becomes

$$Q = \frac{0.271 \times (750 - 300\,(1 + .05))}{500 - 300\,(1 + .05) \times (92 \times .02 - 0.166)} = \frac{117.88}{27.31} = 4.35,$$

and equation 109 becomes.

$$Q = \frac{0.276 \times 300\,(1.00 - .05)}{500 - 300\,(1.00 - .05)(1.674)} = \frac{78.66}{22.90} = 3.42.$$

The larger value, 4.35, is adopted. Since the value of R taken for this computation is much greater than the normal, the regulation will be better than 5 per cent except when the extreme conditions of battery charge are reached. Also, since T is slightly higher than the exact computed value, I_0 normal must be one or two amperes lower than the 300 amperes first assumed, unless the series turns are partly shunted or the rheostat *r* moved to add a slight resistance to the field circuit, which is equivalent to changing the value of Q. With normal condition of battery charge, and $R = .08$, the generator currents will be as follows:

From equation 110

$$I_0 = \frac{4.35 \times 500 + .08\,I_x}{4.35(92 \times .02 + 0.166) + .08} = \frac{2175 + .08\,I_x}{7.282 + .08}.$$

For $I_x = 0$ $I_0 = 295.4$ amperes.
For $I_x = 300$ $I_0 = 299$ amperes.
For $I_x = 750$ $I_0 = 303.6$ amperes.

These figures show that for normal condition of battery charge the regulation is within 2 per cent.

For minimum battery charge and $R = 0.271$, if $I_x = 750$ amperes,

$$I_0 = \frac{2175 + 0.271 \times 750}{7.282 + 0.271} = 314.8 \text{ amperes},$$

or practically 315 amperes, which is within the 5 per cent increase first assumed.

The maximum booster voltage is that required to charge the battery up to 2.7 volts per cell.

Battery voltage on overcharge = 2.7 × 262 = 707 volts.

Deducting generator voltage = 550, the maximum booster pressure = 157 volts.

The maximum current through the booster = 750 − 300 = 450. As this is momentary, 40 per cent of this value is taken.

The capacity of the booster will be 157 × 450 × 0.40 = 28.26 kilowatts.

Since Q = 4.35, the booster field coils will be so proportioned that one volt impressed on the booster field will produce 4.35 volts in the armature. Maximum booster voltage, on regulation, is when the battery voltage falls to 1.65 volts per cell, and I_x = 750 amperes. This will be 550 − 1.65 × 262 = 118 volts. The exciter must be able to give a pressure of 550 volts with 92 × 300 = 27,600 ampere turns, total on the field, and the series coil proportioned to carry 300 amperes, unless a portion of the generator current is shunted, in which case the number of turns will increase and the carrying capacity diminish proportional to the percentage of current shunted.

The exciting energy required by the booster will be between 1 and 1½ per cent of the booster output. This is a maximum when the booster output is a maximum, which occurs when I_x is 750 amperes and the battery voltage is lowest.

Maximum booster volts under this condition = 118 volts.

Current through booster is 750 − 315 = 435 amperes.

Maximum booster output = 435 × 118 = 51.33 K.W.

Taking the required exciting energy as 1 per cent of the booster output, this will be .01 × 51,330 = 513.3 watts. As the voltage impressed on the booster field windings equals the booster armature volts, divided by 4.35, the net electro-motive force at the booster field terminals is $\frac{118}{4.35} = 27.2$ volts. Current, therefore, in the booster field at time of maximum load $= \frac{513.3}{27.2} = 18.87$ amperes.

The volts generated in the exciter armature at this time are 550 + 27.2 = 577.2 volts. The capacity of the exciter, therefore,

must be 577.2 × 18.87 = 10.89 K.W. Taking 40 percent as sufficient for normal rating, this becomes 4.36 K.W. If the exciter is made large enough to give sufficient magnetizing current to produce the maximum booster voltage for full battery charge, its current output will be $\frac{157}{118} \times 18.87 = 25.1$ amperes. Since this voltage must be carried for an hour or more, the capacity of the exciter should be 60 per cent of the product of maximum volts by 25.1 amperes.

The maximum volts across the booster field $= \frac{157}{4.35} = 36.1$ volts.

The exciter volts therefore = 550 + 36.1 = 586.1 volts.

Exciter capacity = 586.1 × 25.1 × .60% = 7.86, say 8 K.W.

For overcharging, the exciting current may be supplied to the booster field direct from the line, the degree of excitation being regulated by the rheostat R. The connections to the field windings are reversed by means of a small hand switch, so that the electro-motive force produced will be in proper direction to charge the battery.

This arrangement reduces the size of exciter necessary to the capacity previously computed for regulation.

As in the case of all the boosters that are discussed, the equations and computations which depend for their value on the battery charge or discharge current must be corrected to include the current supplied by the battery to the motor. Refer to Chapter XXXV.

Theoretically if the exciter and booster field be connected across the battery, the regulation will be greatly improved, as the drop in battery voltage on discharge allows a current flow through the booster field without any augmentation of the exciter voltage, and the increase in load to cause discharge need only be great enough to slightly overcome the battery voltage. Conversely, as the battery voltage increases on charge, the flow through the booster field in the direction to cause charge will take place with a very small decrease in exciter voltage.

In practice, however, it has been found that the system is unstable when connected in this way and for this reason it is not used.

This booster is reversible when connected as before described and depicted in Figs. 186 and 188. It may be transformed into a "constant current," or non-reversible booster, by the simple expe-

dient of reducing the number of ampere turns on the exciter series field and connecting the variable load across the battery, as shown in Fig. 187. In this case the exciter voltage at normal load must be less than that of the line, as the booster voltage is not zero but has a considerable value in the direction of charge, the voltage across the battery being at all times greater than that across the generator bus bars. Therefore, if at normal load the exciter voltage be less than that of the line, a current flow through exciter armature

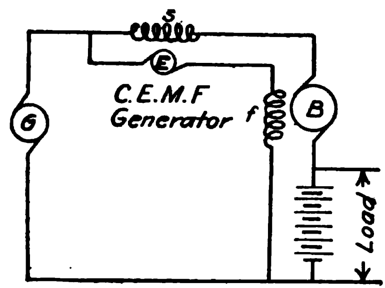


FIG. 187. Counter E.M.F. Booster Connected for Constant Current.

and booster field will take place, producing a booster voltage in the direction of charge. If the external load increases, the exciter voltage opposing the current flow from the line will also be increased, thereby reducing the booster field current and voltage. This is equivalent to a reduction of the power bus bar voltage, which allows the battery to discharge. If the external load be reduced, the exciter voltage is diminished and the current flow through the booster field augmented, producing an increase in booster voltage and causing battery charge.

A complete system for large installations is shown in Fig. 188. The variable resistance in the main dynamo circuit is operated by a motor as shown. By varying this resistance the proportion of current sent through the exciter series field is varied.

The booster is a double commutator machine, as indicated.

In the exciter armature and booster field circuit is inserted the circuit breaker CB, which is shunted by a resistance. In case of excessive current flow through the circuit, the breaker will open, the resistance reducing but not interrupting the exciter current.

The choke coil is to offer opposition to sudden increase or decrease of the generator current with rapid external load fluctuations.

The exciter has a shunt field winding *f*, in addition to the series

field. This field is excited from a small exciting battery which maintains a constant voltage across the terminals of *f*. This field opposes the series field, so that more series field turns are required

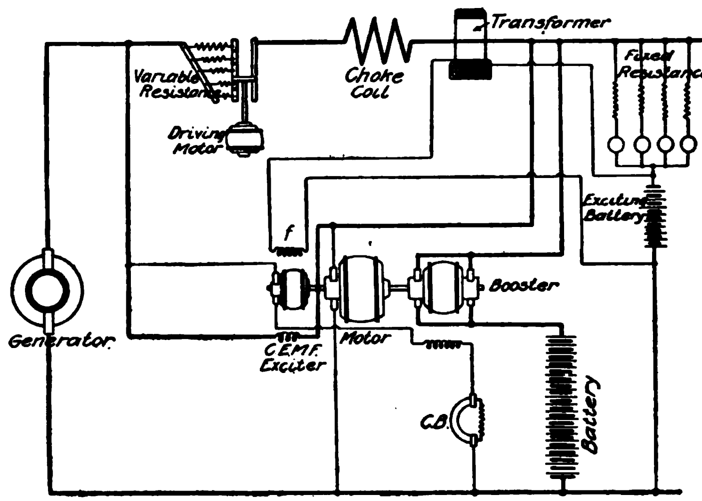


FIG. 188. Complete Connections for Counter E.M.F. Booster System with Auxiliary Excitation.

to produce the required exciter voltage, which means that small changes in generator current will give large changes in the exciter voltage. In series with the circuit from exciting battery to field *f* is the secondary winding of a transformer, which has its primary winding in the generator circuit. The connections and polarities are so related that any sudden current rush from the generator induces a momentary electro-motive force in the secondary of the transformer, which gives an instantaneous impulse to send current through *f* in a direction to cause an excitation that will produce booster voltage in the direction of discharge. Conversely, a sudden reduction in generator current will give a momentary electro-motive force in the direction to produce charge. This arrangement, therefore, serves to make the action of the exciter and booster more rapid than it would be under the action of the exciter series field alone.

In a modification of this system, the exciter voltage produced by any change in generator current is greater than that required to

produce the required booster voltage, and a series winding is put on the exciter which is in opposition to the field produced by the generator current, so that, as the current from the exciter passes through this series winding, the voltage is reduced to its proper value thereby reducing the booster voltage to its required value. The diagram of connections is shown in Fig. 189. S_1 is the field

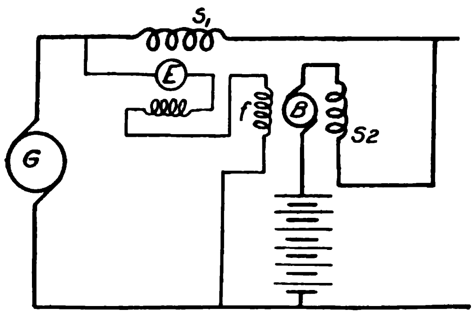


FIG. 189. Counter E.M.F. Booster with Series Winding.

in series with the generator, producing the field of exciter armature E, *f* is the field energized through the exciter armature, and S_2 is a field in series with the exciter and therefore with the exciter current and wound to oppose S_1.

A given change in generator current will produce in E a voltage much greater than that necessary to give the required value to the voltage of B. In other words, the factor Q is greatly increased.

This excess voltage across *f* produces a rapid rise of booster voltage, decreasing the time lag due to self-induction and hysteresis. This causes an almost instantaneous current to flow in the booster field, and as this current rises to its proper value it reduces the exciter voltage by an amount proportional to the ampere turns of the field S_2.

The whole object of this arrangement is to reduce the time element of operation The desirability of a small or negligible time element is set forth at some length in the succeeding chapter. With this modification of Hubbard's booster the size of the exciter is increased.

Since the winding S_1 must produce an initial voltage greater than that actually required for the booster excitation, the size of the exciter must be increased in the ratio of $\frac{V_1}{V_2}$ in which V_1 is

the voltage for normal excitation and V_2 the greater voltage required for reducing the time element.

Highfield's Booster.

The booster devised by J. S. Highfield, of England, belongs also to the separately excited class, and differs from the other boosters before described in that it depends for its operation on the change in voltage at the battery terminals with change in load. It therefore is not suitable to use on regulation with compounded generators unless it be placed far enough away from the power station for the line drop to exceed the voltage rise of the generator, giving as a net result a decrease in voltage with increase in load, or the

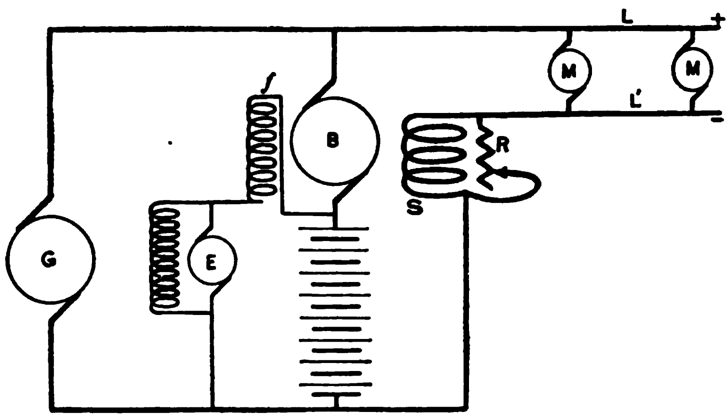


FIG. 190. Highfield's Booster.

series generator fields so arranged with one or two cells in circuit as before described, that a drop always attends a load increase. It, however, is well adapted to work on continuous battery discharge, as a voltage regulator, taking the place of end cells.

Fig. 190 shows, diagrammatically, the connections of this system. G is the generator, E a small direct-current shunt-wound generator, the armature of which is connected to the terminals of the battery passing through *f*, which is the main field of the booster dynamo, B. S is a series field in parallel with the variable shunt R. The voltage of the exciter E is equal to that of the battery under normal condition of load, that is, when the external load is equal to the normal generator output.

If the load should diminish, the generator voltage will rise, tending to send current into the battery. This causes the potential

at the battery terminals to exceed that of E, and a current from the battery will flow through f and E in a direction opposite to the pressure of E. The winding f of B is in such a direction that current flowing against the pressure of E increases the booster pressure, and it assists the generator to charge and at such a rate as is determined by the difference between the battery and exciter voltages.

Conversely, an increase of load, lowering the generator pressure, causes the battery to begin discharge, and as the voltage at the battery terminals falls, E sends current through f to the battery, and the pressure of B is in a direction to assist discharge.

The series field S is to compound the combined battery and generator currents, it increasing the voltage of B on discharge of heavy currents. The two auxiliary machines may be driven in any convenient way, but usually a shunt-wound electric motor is used, the three frames being mounted on one base plate, and the three armatures on one continuous shaft. The booster fields are laminated and worked well below the knee of the magnetization curve, giving a characteristic which is nearly a straight line. In operation there are times when a heavy current may be passing through the armature, and the field is weak and the armature reaction then becomes comparatively excessive. A few series turns are usually wound on the fields to annul the armature reaction. These are not shown in the figure.

The analysis of this system is very simple. The pressure of B is always equal to the drop in the battery on discharge, or increase in battery voltage on charge. That is,

$$V = R\,(I_x - I_0), \tag{111}$$

in which V = booster voltage, R = virtual internal resistance of battery, plus ohmic resistance of connections and booster armature; I_x and I_0 = external and generator currents respectively, and their algebraic difference, the current through the battery, being discharge when the quantity is positive and charge when negative. This equation neglects the current required for the booster motor.

Let

E_0 = generator voltage at no load.

E_A = battery voltage at normal load.

h = drop in generator voltage per ampere.

k = volts induced in booster armature per ampere turn on the field.

Then

$$E_0 - I_0 h = E_A - R\ (I_x - I_0) + V. \qquad (112)$$

But since $V = R\ (I_x - I_0)$, the equation becomes $E_0 - I_0 h = E_A$, whence

$$I_0 = \frac{E_0 - E_A}{h}. \qquad (113)$$

This shows that I_0 varies only when E_A changes, and is greater when E_A is minimum.

The effective voltage sending current through f is the difference between the battery voltage on open circuit and that of charge or discharge. Therefore the voltage across f is at any time equal to the change in battery voltage, which is the same as the booster voltage. Hence the booster armature must induce one volt for each volt potential at the terminals of f.

f may be wound with as many turns as is convenient, the size of the wire being such that the resistance per mean turn is equal to k. This is derived as follows:

If r = resistance of a single turn, $\frac{e}{r} = TI$ = ampere turns on field, e being the volts impressed on the field. $kTI = \frac{ke}{r}$ = volts in booster armature = V. $Vr = ke$, and since $e = V$, $r = k$. (114)

The greater the number of turns and consequently the higher the resistance of the winding, the smaller will be the exciter.

Assume a system in which

$E_0 = 125$ volts.
$E_A = 110$ volts.
$h = .03$.
$k = .02$.
$I_0 = 500$ amperes.
$I_{x\,MAX} = 2000$ amperes.
$R = .01$ ohm.

The maximum battery output (neglecting motor current) is $2000 - 500 = 1500$ amperes.

$I_0 h = 500 \times .03 = 15$ volts.

$E_0 - I_0 h = 110$ volts $= E_A$.

Since the booster voltage must always be equal to $R\ (I_x - I_0)$ and also equal to the voltage impressed on its field, it may be taken as equal to the change in battery voltage from E_A for any given

charge or discharge. Thus when $I_x = 0$, and it is desired that I_0 shall remain constant, the voltage at the battery is increased $.01 \times 500 = 5$ volts = booster voltage in direction of charge, *i.e.*, the battery voltage exceeds that of the line by 5 volts when charged at the rate of 500 amperes, assuming that the cells are far below the point of gassing. Conversely, when there is a discharge of 500 amperes, the battery voltage is 5 volts less than that of the line, and this must be the booster voltage in a discharging direction.

Number of cells, N, $= \frac{110}{2.1} = 52.4$, say 53 cells.

The maximum booster voltage — that of overcharge — $= (53 \times 2.7) - (125 - 200 \times .03) = 24.8$, say 25 volts, 200 amperes being assumed as the maximum current through battery on overcharge.

Maximum current through booster armature = 1500. Booster capacity $= 25 \times 1500 = 37.5$ K.W. If maximum amperes are momentary only, this capacity may be reduced to 40 per cent of the maximum or 15 K.W.

The driving motor has its capacity fixed by the maximum output of 1500 amperes when the battery is at its lowest stage, *i.e.*, 1.65 volts per cell. Booster voltage $= 110 - 53 \times 1.65 = 22.5$ volts. Then motor capacity

$= \frac{22.5 \times 1500 \times 1.34}{80\%} = 45.2$ H.P. The factor .80 is the assumed efficiency of the booster. The power of the motor should be reduced to 40 per cent of the maximum = 18 H.P.

The size of exciter is determined by the resistance of the booster field and the difference between the generator pressure and the normal voltage of the battery. The size of wire for the field winding is fixed by equation 114. Assuming the resistance of the booster field is 4 ohms, the current through exciter armature at maximum booster voltage is $\frac{25}{4} = 6.25$ amperes. The size of the exciter then is $6.25 \times 110 = 687.5$ watts. If there were twice as many turns on the booster field, its resistance would be doubled and the exciter capacity would be only 344 watts.

Storer's Booster.

A third type of separately excited booster is that of Storer,* shown diagrammatically in Fig. 191.

* Amer. Patent No. 695962.

G is a generator, B_1 a booster, E an exciter having series fields, S_1 and S_2, and a shunt field *f* which is connected across the line and is in opposition to S_1 and S_2.

T is the booster field excited from E. As may be seen, the exciter field S_1 is in series with the generator, and S_2 is in series with the line — the whole arrangement of the exciter fields being identical with that of Entz's differential system. Instead of the armature E

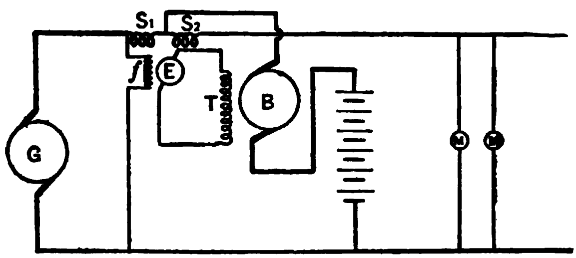


FIG. 191. Storer's Booster.

carrying the battery current, however, it excites the field T of the armature B. The analysis and operation are identical with the Entz system before described, except that a factor Q must be included, which represents the volts produced in armature B, per volt applied at its field terminals.

In booster systems which are separately excited, the exciter is sometimes mounted on the shaft with the driving motor and booster, and these being many times larger than the exciter, the speed of the latter is very slow for so small a machine. Therefore a larger frame is required for the exciter than for a machine of the same output running at its proper speed. The tendency at the present time (1910) is to drive the exciter and booster by separate motors so that each machine may run at its commercially economical speed. Although this arrangement requires two motors instead of one, the total cost is reduced and the efficiency is slightly increased.

CHAPTER XXXIV.

EXTERNALLY CONTROLLED AUTOMATIC BOOSTERS.

WITH the exception of Hubbard's "counter E.M.F." system, none of the forms of boosters before described are now (1910) being marketed in America, and they are important only in that many examples are still in operation. They have been superseded by the externally controlled types because of the cheapness, efficiency, closeness of regulation and ease of adjustment of the latter forms.

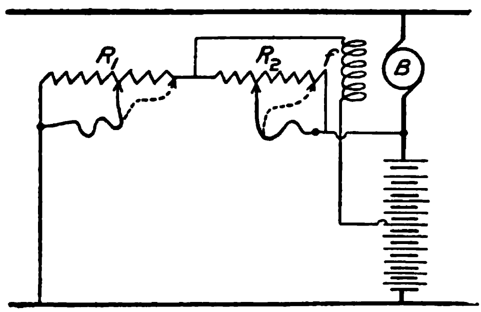


FIG. 192. General Diagram of Connections for Externally Controlled Booster.

The externally controlled booster is simply an ordinary shunt-wound generator with its field winding connected to an automatic regulator which is responsive to load changes, and which varies the booster excitation correspondingly.

The arrangement common to three of the systems which are described hereafter, namely, the *Entz*, the *Lyndon* and the *Bijur*, is shown in Fig. 192.

B is the booster armature, *f* the booster field; R_1 and R_2 are two variable resistances which are connected together and to one terminal of the booster field at a common point. One terminal of one resistance is connected to the positive side of the battery, and one terminal of the other resistance is connected to the negative side of the battery. One terminal of the field *f* is connected to the middle point of the battery. Under conditions of normal load,

when there is neither battery charge nor discharge and the booster voltage is zero, the resistances have an equal value and both are reduced below their maximum value, or partially short-circuited. Obviously, a small current will flow from the positive to the negative side of the battery through the two resistances, and the drop through either resistance is equal to one-half the battery voltage. Therefore, at the common junction of the two resistances and booster field terminal, the potential is exactly equal to that of the middle point of the battery, to which the other terminal of the field winding is connected.

Since there is no potential difference between the two terminals of the field coil, there is no current flow, no excitation of the booster field and the booster voltage is zero.

If, however, the resistance of R_1 be decreased and that of R_2 increased, the potential of the junction point, J, is brought nearer to that of the negative side of the battery and current will flow from the middle point of the battery, through the field coil *f* and through the resistance R_1 (now decreased), to the negative side of the battery, producing a booster excitation and pressure in a direction to cause discharge. Also, the greater R_2 becomes and the less R_1, the greater will be the difference in potential between the middle battery point and the common junction point J, and, in consequence, the greater will be the booster excitation and voltage.

Conversely, if R_2 be diminished and R_1 be increased, the potential of point J is brought near to that of the positive side of the battery and current will flow from the positive side of the battery, through R_2 (reduced) and through booster field *f* to the middle point of the battery. This will produce a booster excitation in a direction opposite to that produced when R_1 is diminished, and will cause a booster voltage in a direction to charge the battery. The essential differences among the several types described in this chapter reside in the methods to control the variation of the regulating resistances and cause them to automatically change with load changes on the system in accordance with the requirements to produce charge or discharge. With the exception of the Thury booster, all the external controlling devices are worked by an electro-magnet in series relation with the generator current, its pull being opposed by some mechanical force. The magnet pull due to normal generator current just balances the opposing force. With increase or reduction in generator current, the magnet

pull will become greater or less than the opposing force causing a movement of the parts which changes the values of the resistances to produce charge or discharge of the battery. The principal advantages of this type over those which are made automatic by opposing field windings and previously discussed are:

(1) The booster may be made of a standard shunt-wound dynamo instead of requiring special field windings and a special frame to accommodate them. Therefore the booster costs less and the installation of a plant is not delayed in waiting for the delivery of a special machine.

(2) The sensitiveness of regulation may be varied, at will, to suit changing conditions.

(3) By means of mechanical stops the battery discharge or charge may be limited, allowing the overload capacity of the generators to carry any load in excess of that which the battery can safely carry.

(4) The working magnet, which is put in series with the generator circuit, can be located in any convenient place for connection to the bus bars, and heavy conductors leading out to the booster are not required, thus saving a considerable expense in installation and energy loss in operation.

(5) The degree of regulation is independent of the size of the booster and can be made to come within limits that could not be obtained with pole-wound boosters unless excessively large frames were used, which would make the efficiency low and the cost prohibitive.

(6) "Overtravel," or the initial application of a high field voltage to overcome the time lag of self-induction, which voltage decreases to its proper value as the booster voltage rises, can be obtained. This means quicker and better regulation than is possible without this feature.

When just the voltage necessary is impressed on the booster field, the time required to bring up the booster voltage is appreciable, due to self-induction and hysteresis lag. Referring to the curves shown in Fig. 193: With a given resistance and inductance, the final value of the current due to any steady electro-motive force is reached in a given time, which time is a constant for any electro-motive force E applied, the formula being

$$i = i_0\left(1 - e^{-\frac{rt}{L}}\right), \qquad (115)$$

in which i = current in coil after any time t, $i_0 = \left(\frac{E}{r}\right)$ which is the maximum value of i, r = resistance, t = time in seconds after

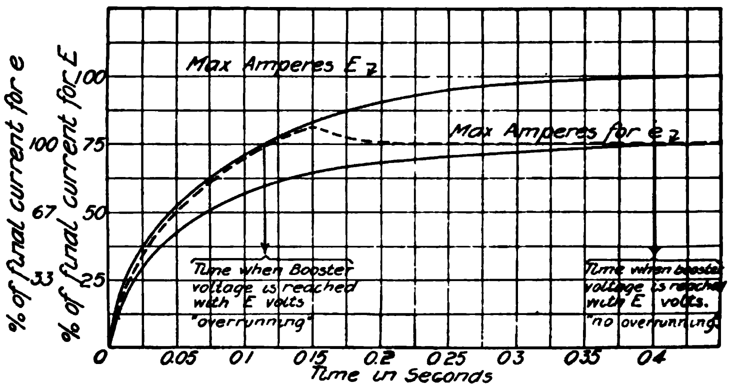


FIG. 193. Curve of Current Increase with Time in Inductive Circuit.

making the circuit, e = base of Naperian logarithms, L = self-induction of the coil in henrys. Solving for t,

$$t = \frac{\frac{L}{r}\log\frac{i_0}{i_0 - i}}{\log e}. \tag{116}$$

This equation shows that the time of reaching the final maximum value of current is independent of the value of the applied electro-motive force.

If a voltage higher than that required for regulation be impressed on the booster field, the booster voltage will rise more quickly to its desired value, and the booster action will take place with a corresponding decrease in time lag. The booster voltage and battery discharge will then become slightly higher than necessary and the controller will retreat from the extreme position it has taken, coming back to a point corresponding to the actual excitation required. The rise of booster voltage beyond its proper value and subsequent recession are indicated by the dotted curve lying adjacent to the curve of higher voltage.

By a comparison of these curves it is obvious that more rapid changes are produced by "overtravel" and consequently better regulation.

There are certain conditions and equations which are common to all externally controlled boosters, and the analysis of the current and voltage changes in the regulators is the same for the three systems immediately following.

In computing the sizes of boosters for these externally controlled systems, use the same methods as in determining the sizes of plain shunt boosters. If the booster requires an excitation greater than 400 watts to produce maximum voltage, a small exciting dynamo is necessary, which supplies the proper field current to the booster. The field of the exciter is controlled by the external regulator. The size of the exciter must be such as to give full excitation at the time of greatest booster voltage on regulation, which will be when the battery is nearly exhausted and discharging maximum current, except in certain cases where the range of voltage on regulation must be such as to include sending full charge into the battery when the voltage is 2.6 or 2.7 volts per cell. Under this condition the maximum booster and exciter voltages are fixed by the maximum battery voltage.

The computation of the booster and motor constants of these systems where an exciter is used, is as follows;

Let E_A = Battery voltage on open circuit.
E_0 = Generator voltage on no load.
h = Increase in generator voltage per ampere of output — positive for increase (over compounded) and negative for decrease (shunt).
I_0 = Generator current.
I_x = Current to external load.
V = Booster voltage.
R = virtual resistance of battery and booster circuit.

At any time, the line voltage is equal to that of the battery, minus resistance drop through battery plus booster voltage. Then the equation of electro-motive forces (neglecting the motor current) is

$$E_0 + I_0h = V + E_A - R\,(I_x - I_0). \qquad (117)$$

Booster voltage $V = E_0 + I_0h - E_A + R\,(I_x - I_0)$. (118)

Booster capacity $= V\,(I_x - I_0) \times 0.40$ (119)

$$= [E_0 + I_0h - E_A - R\,(I_x - I_0)] \times [I_x - I_0] \times 0.40.$$

The factor 0.40 indicates that 40% of the maximum booster output is sufficient for the capacity rating of the machine.

V is maximum when charging the battery up to highest voltage. If an exciter be used and the booster excitation is S per cent of the booster output, the exciter must supply $\frac{SV}{100}(I_x - I_0)$ watts.

$$(120)$$

$$\text{Size of exciter} = \frac{SV_{MAX}}{100}(I_{x\,MAX} - I_0). \qquad (121)$$

If for Q volts impressed on the field of the booster 1 volt will be generated in the booster armature, then exciter volts $v = VQ$.

Hence exciter current delivered to booster field

$$C = \left(\frac{SV}{100}\right) \times \frac{(I_x - I_0)}{VQ} = \frac{S}{100\,Q}(I_x - I_0). \qquad (122)$$

If the energy required to supply the exciter fields be s per cent of the exciter output, then this energy

$$w = \frac{s}{100} \times \frac{SV}{100}(I_x - I_0) = \frac{sSV}{10{,}000}(I_x - I_0). \qquad (123)$$

which is the energy through the regulator.

If one volt is generated in the exciter armature for q volts impressed on the field, then the volts across the field terminals of the exciter will be vq.

Exciter field current,

$$c = \frac{SsV}{10{,}000} \times \frac{(I_x - I_0)}{vq} \qquad (124)$$

Since $v = VQ$,

$$c = \frac{Ss}{10{,}000\,Qq}(I_x - I_0). \qquad (125)$$

All these equations assume straight characteristics.

The size of the motor to drive the booster will be that necessary for maximum discharge when the battery is nearly exhausted, the voltage per cell being about 1.65, which is 0.45 volt less than the normal open circuit voltage. If N = number of cells in the battery, then $V = 0.45\,N$, and the booster output $= V(I_x - I_0) = 0.45 \times N\,(I_x - I_0)$. (126)

Then size of the motor $= \frac{1}{.85} \times 0.45\ N\ (I_x - I_0)\ 0.40$, K.W.

$$(127)$$

the factor .40 representing the percentage of the maximum output that is sufficient for the normal rating of the machine. Fac-

tor .85 = assumed efficiency of the booster. All these equations must be corrected for motor current as set forth in the succeeding chapter.

For all controllers having two inversely varying resistances the following general analysis obtains, under the conditions that the resistances are connected across a certain number of battery cells with the booster field coil connected to the cell midway between the extreme cells across which the resistances are connected.

The voltage across *each* resistance is $e - mn\,(I_x - I_0)$, (128) in which e = voltage on open circuit of group of cells across which one resistance is connected and $2\,e$ = voltage of the group across which the pair of resistances is connected.

m = virtual internal resistance *per cell.*

n = number of cells in a group.

Where the voltage of the cells is known for various conditions of charge and discharge, the value ϵn may be substituted for $e - mn\,(I_x - I_0)$ across each resistance, ϵ being the volts per cell.

To determine R_1 and R_2 the following conditions must be fulfilled.

R_1 minimum must not exceed a value such that when the exciter field current c is maximum, cR_1 is less than $e - nm\,(I_x - I_0)$. (129)

When $c = 0$, and $R_1 = R_2$, maximum value of $R_1 + R_2$ must be such as to prevent a large current flow through the resistances.

Minimum value of R_1 must be produced by a change in magnet pull, corresponding to a change in current flow through controller magnet, which is within the limit of regulation to be allowed.

For any value of c the resistance R_1 must be

$$R_1 = \frac{e - nm\,(I_x - I_0) - v}{c + i}, \tag{130}$$

in which i = current through R_1 and R_2 and v = voltage applied across the exciter (or booster) field. The term ϵn may be substituted for $\epsilon - mn(I_x - I_0)$, in which ϵ = volts per cell for the condition of battery charge and current flow that may be assumed for computation. The equation then becomes

$$R_1 = \frac{\epsilon n - v}{c + i}. \tag{131}$$

Since the drop through R_2 is equal to the voltage impressed across it,

$$R_2 i = \epsilon n \text{ and } i = \frac{\epsilon n}{R_2}. \tag{132}$$

Also,
$$R_1(c+i)+v=\epsilon n. \tag{133}$$
$v = cr$, r being the resistance of the exciter (or booster) field. Substituting the value of i,

$$\epsilon n = R_1\left(c+\frac{\epsilon n}{R_2}\right)+v, \tag{134}$$

$$v = cr = \epsilon n\left(1-\frac{R_1}{R_2}\right) - R_1 c, \tag{135}$$

whence

$$c = \frac{\epsilon n\left(1-\frac{R_1}{R_2}\right)}{R_1+r} \tag{136}$$

and

$$v = cr = \frac{r\epsilon n\left(1-\frac{R_1}{R_2}\right)}{R_1+r}. \tag{137}$$

Also,
$$c^2 r = \text{watts in field} = w.$$
$$r = \frac{w}{c^2}.$$

Substituting this value of r in equation 136,

$$c = \frac{\epsilon n\left(1-\frac{R_1}{R_2}\right)}{\frac{w}{c^2}+R_1},$$

whence

$$c = \frac{\epsilon n\left(1-\frac{R_1}{R_2}\right)}{2\,R_1} \pm \sqrt{\left(\frac{\epsilon n\left(1-\frac{R_1}{R_2}\right)}{2\,R_1}\right)^2 - \frac{w}{R_1}} \tag{138}$$

and

$$v = \frac{w}{c}.$$

This equation may be more easily used by putting

$$\epsilon n = \Delta, \text{ and } \left(1-\frac{R_1}{R_2}\right) = \theta;$$

the equation then becomes

$$c = \frac{\Delta\theta}{2\,R_1} \pm \sqrt{\left(\frac{\Delta\theta}{2\,R_1}\right)^2 - \frac{w}{R_1}}. \tag{139}$$

It is important to note that the watts w, supplied to the field, cannot be greater than

$$\frac{(\epsilon n)^2\left(1 - \frac{R_1}{R_2}\right)^2}{4\ R_1}, \tag{140}$$

for if w is greater than this, the quantity under the radical sign in equation 138 becomes negative and therefore imaginary. Also, since the sign before the radical may be either plus or minus, there are two values of c that will fulfill the conditions of the equation.

When the watts are known and the maximum value of R_2 is given, the value of R_1 is found as follows.

From the condition given in equation 140, the maximum possible value of R_1 is such that

$$4\ R_1 w = (\epsilon n)^2\left(1 - \frac{R_1}{R_2}\right)^2. \tag{141}$$

Solving,

$$R_1 = R_2 + \frac{2\ R_2^2 w}{(\epsilon n)^2} \pm \sqrt{\left(R_2 + \frac{2\ R_2^2 w}{(\epsilon n)^2}\right)^2 - R_2^2}. \tag{142}$$

This equation apparently gives two values of R_1, but if the positive sign before the radical is used the value of R_1 thus found will be greater than that of R_2, which means that R_1 is negative, and this is an imaginary condition. Therefore the minus sign before the radical is the one to be used.

All the foregoing equations are based on the resistances being connected to the battery terminals. If, however, the resistances be connected across the line, the outside potentials will remain unchanged. The potential of the middle battery point, however, will shift with charge and discharge, so that the voltages impressed across R_1 and R_2 will vary. For this condition the proper point to connect the battery terminal of the exciter field is not the middle of the battery but some point nearer to the end connected to the booster than to the end connected to the line.

This point is found as follows: Call the end of the battery connected to the line point A, the point to which the exciter (or booster) field terminal is connected, B, and the end of the battery connected to the booster, point C. The maximum voltage between A and B should be (approximately) equal to the maximum voltage between B and C. Also the minimum voltage between A and B should be equal to the minimum voltage between B and C.

The maximum voltage between A and B is when the battery is near full charge, the maximum regulating pressure being 2.4 volts per cell. The maximum voltage between B and C is when the battery is nearly discharged and has fallen to 1.65 volts per cell, the booster adding its maximum voltage to the battery under this condition.

The minimum voltage between A and B is when the battery voltage is at its minimum pressure of 1.65 volts per cell on discharge. The minimum voltage between B and C is when the battery voltage is a maximum of 2.4 volts per cell on charge and the maximum charging voltage of the booster is deducted from that of the battery.

Call n the number of cells between A and B.

Call n_1 the number of cells between B and C.

Call E the voltage of the main circuit.

Then $$2.4\,n = \mathrm{E} - 1.65\,n_1 \qquad (143)$$

and $$1.65\,n = \mathrm{E} - 2.4\,n_1. \qquad (144)$$

Solving, $$n = 0.248\ \mathrm{E}. \qquad (145)$$

Thus for E = 550 volts n = 136.4 cells, or say 136 cells, and $n_1 = \mathrm{N} - n$.

If N = 262 cells, n_1 = 126 cells.

The resistances R_1 and R_2 must be connected to the circuit and to the exciter field in such a manner that reduction of R_1 causes discharge, and R_1 is connected between B and C, while R_2 is connected between A and B and a reduction in its resistance causes charge. In this way the maximum values of the voltages across R_1 and R_2 become useful in producing the maximum booster voltage to discharge or charge.

Going back to equation 131, and taking R_1 R_2, r, v, c, ϵ, w and n as given in equations 122 *et seq.*, the equations for the field winding thus connected are as follows:

$$R_1 = \frac{\epsilon n - v}{c + i}.$$

For this case, however, ϵn becomes $\mathrm{E} - \epsilon n$; hence

$$R_1 = \frac{\mathrm{E} - \epsilon n - v}{c + i}, \qquad (146)$$

ϵn being the voltage across R_2 and $\mathrm{E} - \epsilon n$ the voltage across R_1.

Also, $i = \dfrac{\epsilon n}{R_2}$ as in equation 132.

Whence

$$R_1 = \frac{E - \epsilon n - v}{c + \frac{\epsilon n}{R_2}}, \tag{147}$$

$$E - \epsilon n = R_1\left(c + \frac{\epsilon n}{R_2}\right) + v.$$

Putting $v = cr$ and solving,

$$c = \frac{E - \epsilon n\left(1 + \frac{R_1}{R_2}\right)}{R_1 + r}. \tag{148}$$

Taking $r = \frac{w}{c^2}$, substituting this value of r in equation 147, and solving,

$$c = \frac{E - \epsilon n\left(1 + \frac{R_1}{R_2}\right)}{2\,R_1} \pm \sqrt{\left(\frac{E - \epsilon n\left(1 + \frac{R_1}{R_2}\right)}{2\,R_1}\right)^2 - \frac{w}{R_1}}. \tag{149}$$

If

$$w > \frac{\left(E - \epsilon n\left(1 + \frac{R_1}{R_2}\right)\right)^2}{4\,R_1},$$

the quantity under the radical is imaginary and the watts assumed are greater than the regulator can supply to the field winding. The maximum value of w, then, is equal to the term in parenthes is, under the radical in equation 149. Therefore,

$$w = \frac{\left(E - \epsilon n\left(1 + \frac{R_1}{R_2}\right)\right)^2}{4\,R_1} \tag{150}$$

shows the maximum value of w for given values of R_1, R_2, E and n.

The pull of an electro-magnet is proportional to the square of the ampere-turns and to the first power of the area of the core.

Formula for pull in pounds avoirdupois is

$$P = \frac{B^2A}{72{,}134{,}000}, \tag{151}$$

in which

B = number of lines per square inch in the air gap,
A = area of core in square inches,
72,134,000 = constant derived by multiplying $8\pi \times$ (no. of dynes in 1 pound) $\times$ (no. of sq. cms. in 1 inch).

$$B = \frac{IT}{Z},$$

in which

I = current in amperes,
T = number of turns,
Z = magnetic reluctance.

Whence
$$\frac{I^2\left(\frac{T}{Z}\right)^2 A}{72{,}134{,}000} = \text{pull.}$$

Calling
$$\frac{\left(\frac{T}{Z}\right)^2 A}{72{,}134{,}000} = \gamma,$$

then
$$I_0^2\gamma = \text{pull for current } I_0. \tag{152}$$

If the increase in generator current to produce a given pull is to be within ϕ per cent of the normal current, the maximum generator current $= I_0 + \frac{\phi I_0}{100}$, and the pull for this current will be

$$I_0^2\left(1 + \frac{2\phi I_0}{100} + \frac{\phi^2}{10{,}000}\right)\gamma, \tag{153}$$

and the increase in pull above that due to I_0 will be

$$\left(\frac{2\phi}{100} + \frac{\phi^2}{10{,}000}\right) I^2\gamma. \tag{154}$$

The increase in pull must be such as to give the required reduction in resistance of R_1 to produce the booster voltage corresponding to the battery discharge $(I_x - I_0)$.

If for maximum value of $(I_x - I_0)$ and a regulation within ϕ per cent, the increase in pull is to be p pounds, the normal pull P for $I_0 = I_x$, is determined as follows:

Ratio of P to $P + p$ = ratio of I^2 to $I^2\left(1 + \frac{2\phi}{100} + \frac{\phi^2}{10{,}000}\right)$,

or
$$(P + p)\, I^2 = PI^2\left(1 + \frac{2\phi}{100} + \frac{\phi^2}{10{,}000}\right).$$

Whence
$$P = \frac{p}{\left(\frac{2\phi}{100} + \frac{\phi^2}{10{,}000}\right)}. \tag{155}$$

As a practical example common to all externally controlled booster systems assume the following conditions:

$E_0 = 500$ volts.
$h = 0.083$ volt.
$I_0 = 600$ amperes.
I_x maximum $= 1800$.
$R = 0.035$.
$\phi = 5$ per cent.
E_A on open circuit $= 550$ volts.

$$N = \frac{550}{2.1} = 262 \text{ cells.}$$

$$m = \frac{R}{N} = \frac{0.035}{272} = 0.0001287.$$

Then for $I_x = 600$ amperes, from equation 118,

$$V = 500 + 0.083 \times 600 - 550 + 0.035\,(600 - 600) = 0.$$

For $I_x = 1800$ amperes,

$$V = 500 + 50 - 550 + 0.035\,(1800 - 600) = 42 \text{ volts.}$$

This is the value of the booster voltage for the maximum discharge of 1800 amperes when the battery is well charged.

V_{MAX} for very low stage of battery charge and maximum discharge, the terminal voltage per cell being about 1.65 volts, will be

$$V = 500 + 0.083 \times 600 - 262 \times 1.65 = 118 \text{ volts.}$$

In this case 262×1.65 is equal to battery voltage less drop due to discharge current.

The maximum booster voltage for charging $= (262 \times 2.7) - (500 + 200 \times 0.083) = 200$ volts, the term 200×0.083 being the generator voltage due to the compound winding when a charging current of 200 amperes is flowing.

In practice, the generator field rheostat would be set to bring the pressure up to 550 volts, on overcharge, so that the actual booster voltage would be 157 volts. Adopt 160 volts.

Since maximum current through the booster (neglecting motor current) is $1800 - 600 = 1200$ amperes, the booster capacity $= 1200 \times 160 = 192$ K.W. 40 per cent of this will be large enough, as the duration of the maximum current is not longer than a minute or two. The size of the booster is, therefore, $192 \times 0.40 = 76.8$ K.W., and it must deliver a maximum pressure of 160 volts.

The specified regulation of 5 per cent is intended to obtain even when the battery is practically exhausted. In this case the booster

pressure = 118 volts as before computed. The excitation required by the booster field will be about 1.5 per cent to produce maximum voltage. If a compensating winding or an inter-pole machine is used, this excitation will depend only on the voltage to be produced and not on the current output.

Assuming that an 80-K.W. booster be adopted, the maximum excitation will be $0.015 \times 80{,}000 = 1200$ watts.

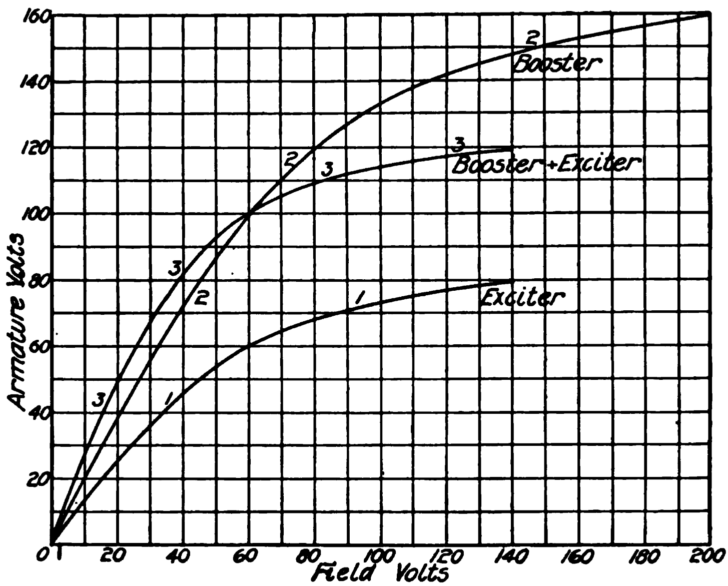


FIG. 194. Booster and Exciter Characteristics.

In the externally controlled systems the boosters are worked up to higher magnetic densities than are the pole-wound or self-exciting machines, and consequently the characteristics must be taken into account. Fig. 194 is a series of three curves, of which 1 and 2 are the characteristics of the exciter and booster respectively. Curve No. 3 is the combined exciter and booster characteristics, any point on which shows the booster volts for a given pressure applied to the field of the exciter. Of course, if the exciter is not used, curve No. 2 is the only one to be plotted.

From the combined characteristic it is seen that to produce the 118 volts at the booster armature requisite for maximum discharge when the battery is nearly exhausted, approximately 112

volts must be impressed across the exciter field. If the booster and exciter be designed for this maximum condition, all intermediate steps may be neglected.

As previously found, the watts excitation to produce 160 volts at the booster armature is 1200 watts, and from characteristic curve No. 2 it is seen that a pressure of 200 volts must be applied at the booster field terminals to produce the required booster voltage. The booster field current, therefore, will be $\frac{1200}{200} = 6$ amperes and the resistance of the booster field $= \frac{200}{6} = 33.33$ ohms.

A pressure of 76 volts across the booster field is required to produce a booster armature pressure of 118 volts, which corresponds to a field current of $\frac{76}{33.3} = 2.28$ amperes, and the energy is $76 \times 2.28 = 173$ watts. This is the required output of the exciter for maximum booster voltage on regulation. The exciter may be made with a capacity 40 per cent of the above required output, but owing to its very small size a 200-watt exciter would be used, for mechanical reasons.

To impress 76 volts across the booster field, the exciter field must have impressed on it 112 volts, and this is the pressure the regulator must deliver to the exciter field when the generator current has increased 5 per cent, or from 600 to 630 amperes. The watts in the exciter field will be about 6 per cent of the exciter output. This large percentage excitation is due to the very small size of the machine.

6 % of 200 watts = 12 watts = energy in exciter field at time of maximum output.

Current in exciter field $= \frac{12}{112} = 0.1071$ ampere.

Resistance of exciter field $= \frac{112}{0.1071} = 1045$ ohms.

The regulator must provide for this current and the 112 volts necessary to pass the current through the resistance, as will be set forth in the analyses of the several systems described in this chapter.

The size of the motor for this booster will be fixed by the maximum output at any time.

Maximum output of booster = 1200 amperes at 118 volts = 141.6 K.W.

Take efficiency of booster as 90%.

Then motor output $= \frac{141.6}{.90} = 157.3$ K.W. $= 210.8$ H.P.

Since the maximum output lasts only a few moments, 40 per cent of this capacity will be ample. Size of motor therefore = 84 H.P.

All the foregoing computations are based on the exciter being able to produce only the booster voltage required for maximum battery discharge, and the quantities must be increased in proper ratio if higher voltages for overtravel are to be delivered. Thus, if the maximum exciter pressure is to be equal to twice that required to produce the booster pressure for battery discharge for a 550-volt circuit, and the constants are as assumed in the foregoing general example, the exciter will have to give a pressure of $2 \times 76 = 152$ volts. This will double its size, making it $2 \times 173 = 346$ watts, or say 350 watts. Also, the exciter field should have impressed across it double the voltage necessary to produce the required booster voltage, or what amounts to the same thing, the field should be wound with a larger size of wire so that the ampere-turns for a given impressed voltage across the field are about twice the amount necessary to produce 152 volts in a 350-watt machine. The field energy in this case, for full excitation of the exciter, will be $0.06 \times 350 = 21$ watts, and the field would be wound to take $2 \times 21 = 42$ watts with 112 volts impressed across its terminals.

With this proportioning of apparatus, if a 5 per cent change in generator current moves the regulator to such a position that 112 volts are impressed on the exciter field, the exciter voltage quickly rises to 152 volts, and tends to greatly exceed this pressure as the exciter field has a constantly increasing current through it, that would rise finally to double the value required to produce 152 volts if it were not for the "retreat" of the controller. This 152 volts quickly applied to the booster field brings up the booster voltage with only an infinitesimal time lag, and the "retreat" of the controller prevents the booster voltage from rising but little above the proper pressure for battery charge or discharge. When conditions of equilibrium are established, and the maximum required regulation voltage of 118 volts is delivered by the booster, the exciter is supplying 2.28 amperes to the booster field at 76 volts, and the field excitation of the exciter is determined from the characteristic of a 350-watt machine capable of supplying 152 volts.

"Constant current" or non-reversible boosters are regulated by

the same character of controllers having only a single resistance. The general scheme of connections is as indicated in Fig. 195. The current from the generator passes to the fluctuating load MM through controller magnet C and booster armature B. The exciter field *f* is energized by current from the bus bars or from a group of battery cells.

The pull of the magnet tends to increase the amount of resistance R in circuit with the booster field coil, and a spring, S, or equivalent mechanical force, opposes the magnet pull, these two opposing forces being in equilibrium when the current taken by the external load MM is equal to the average of the varying currents required by this load.

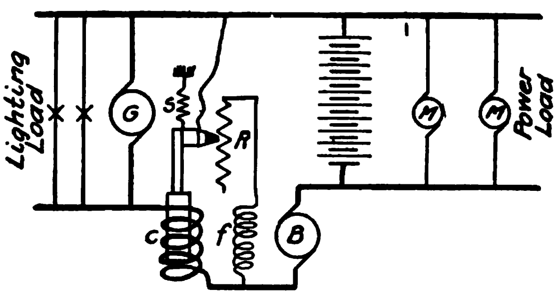


FIG. 195. Connections of Controller for Non-Reversible Booster.

An increase in the external load is followed by an increase in current through C. The magnet overpowers the opposing force, causing the resistance in the field circuit to increase and reducing the booster voltage. This diminishes the pressure between the power bus bars and the battery discharges. The converse action on reduction of load is obvious.

In computing non-reversible, externally controlled boosters, take the ampere output as the average current, and maximum voltage as that necessary to charge the battery to its maximum pressure. The computation of the controller resistance is simply to determine the maximum and minimum currents through the booster field, and arrange the resistance to give these required currents, without the controller having to move through a greater range than that produced by the change in magnet pull due to the percentage change in booster current which has been fixed as the degree of regulation.

In the Entz controller, smaller voltages across the booster fields are used than those assumed in the foregoing example. This does not change the capacity of any of the machines, but makes the current through the exciter field greater and the resistance lower to correspond with the lower voltage impressed on the field.

With the Lyndon and the Bijur controllers, it is sometimes found desirable to put a resistance in series with the exciter field. This is used to adjust the field resistance of a standard machine to the conditions to be met on regulation, as required by equation 137

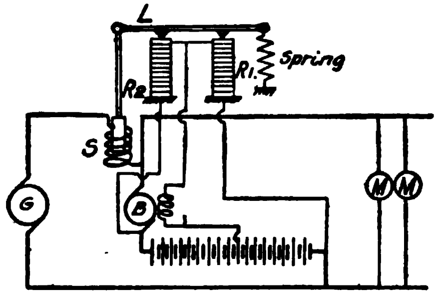


FIG. 196. Entz Externally Controlled Booster, Diagram of Connections.

when the resistance of the standard field is lower than the necessary value.

The Entz Externally Controlled Booster.*

This form is shown diagrammatically in Fig. 196. R_1 and R_2 are two resistances made up of piles of carbon discs. The resistance of these piles changes greatly with pressure. L is a lever resting on the tops of the piles R_1 and R_2. At one end of the lever is the magnet S, which has its winding in series with the generator circuit. At the other end of L is a spring which pulls L downward. When the pull of the magnet is equal to that of the spring the pressure exerted by L on carbon pile R_1 is equal to that on R_2, and the resistances of the two piles are equal.

The booster field *f* has one terminal connected to the middle point of the battery, and the other terminal is connected to a wire which joins the upper ends of the two carbon piles.

The lower end of R_1 is connected to the positive side of the battery, and the lower end of R_2 to the negative side.

The drop through R_1 plus R_2, *i.e.*, from the positive to the nega-

* Amer. Pat. No. 763168, June 21, 1904.

tive side, is equal to the potential of the battery, and therefore when R_1 is equal to R_2 the drop through either is equal to one-half the potential of the battery; hence the potential of the terminal of the field coil *f*, connected to the upper ends of the resistances, is midway between the potentials of the positive and negative battery terminals.

Since the other terminal of coil *f* is connected to the middle point of the battery, its potential is also midway between the total battery potential, from which it follows that when R_1 and R_2 are equal there is no difference of potential between the field coil terminals, consequently no excitation, and the booster potential is zero.

If the external load should increase, a small increase in generator current will cause a stronger magnet pull, increasing the pressure on R_2 and reducing it on R_1, thereby decreasing the resistance of R_2 and increasing that of R_1. The drop through R_2 becomes much

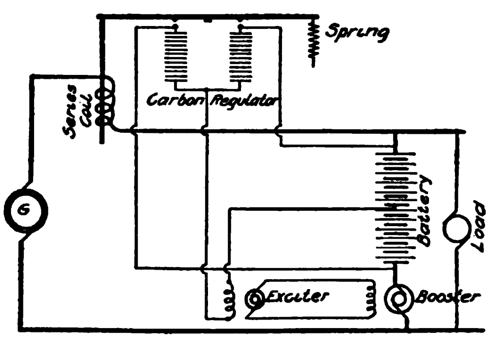


FIG. 197. Entz Booster with Exciter, Diagram of Connections.

less than half the potential across the battery, and consequently there is a potential across the field winding *f* to cause current flow from the middle point of the battery through the winding, through the diminished resistance R_2 to the negative side of the battery. This produces a booster pressure in a direction to discharge the battery and cause it to assist the generator to supply the load demand.

Conversely, if the external load MM should decrease, the diminished pull of the magnet, due to the slight decrease in generator current, allows the spring pull to predominate, the resistance of R_1

is decreased, while that of R_2 is increased. The field *f* becomes excited by current flow from the positive side of the battery through the diminished resistance R_1, through field *f*, to the middle point of the battery. This sets up a pressure in the booster armature

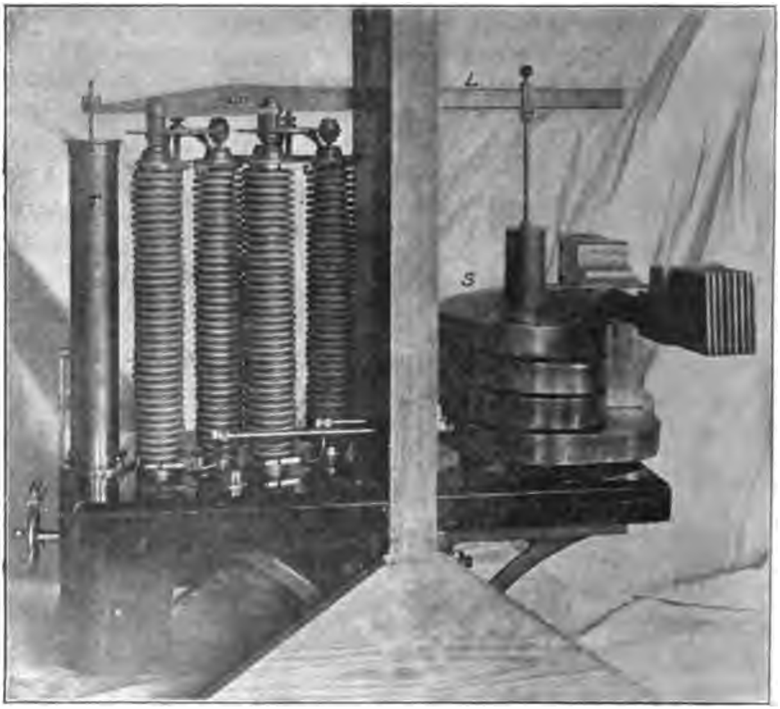


FIG. 198. Entz Booster Controller.

to charge the battery, the difference between the normal generator output and the load demand being thus absorbed.

Owing to the comparatively small change in the pressures which the magnet S exerts, and the thereby limited size of the carbon piles, this system is only directly applicable to small boosters. Where large machines are to be controlled, the carbon piles regulate the field of a small exciting dynamo, which in turn supplies the field magnets of the booster. Obviously, the booster voltage will exactly follow the changes in the exciter pressure both in direction and degree.

The connections of this booster with exciter are shown in Fig.197. The regulator is depicted in Fig. 198. The heavy magnet coil carrying large currents from the dynamo circuit is shown on the right together with the working core. On the left may be seen the tube in which the retracting spring is placed, while the carbon

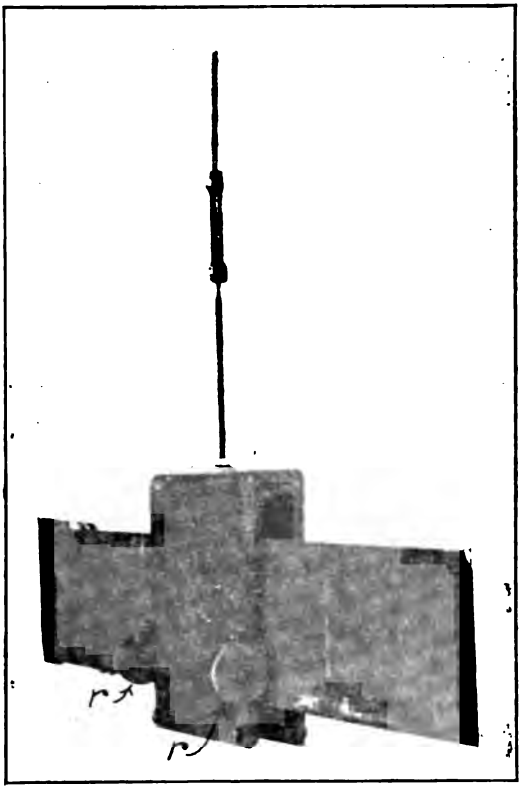


FIG. 199. Bus Bar Magnet.

piles are shown between the tube and the coil. The hand wheel W is for changing the spring tension and thereby varying the adjustment of the regulator.

Fig. 199 shows a form of magnet much used for controlling regulators of this kind. It consists of a piece of strap iron bent to form a narrow rectangular opening between parallel sides, as shown. This is placed over the generator bus bar and connected mechani-

cally to the regulator through an adjustable rod. The current in the bus bar tends to draw the iron piece or "horseshoe" further over it, the pull being proportional to the square of the current flowing. The small rollers *r*, *r* are for the purpose of preventing either side of the shoe from coming in contact with the bus bar and holding to it magnetically. These rollers are placed on both sides, those behind the bus bar not being visible in the picture.

In this system the regulation is independent of the size of the booster and depends only on the relative magnitude of the forces acting on the carbon piles and the resistance of the piles to compression. Within certain limits, very slight changes in pressure

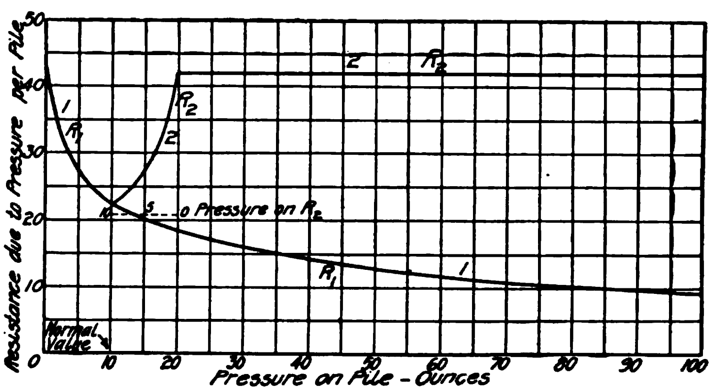


FIG. 200. Curve of Resistance and Pressure on Carbon Piles.

cause great changes in resistance, and the variation of generator current with changes in external load is practically negligible. When a certain point in compression of the piles is reached, the increase in pressure to secure appreciable reduction of resistance must be considerable. Therefore, to obtain close regulation throughout the range of automatic working, the magnet and the spring must be very powerful, so that a small percentage change in pull amounts to a considerable change in pressure.

The general relation between resistance and pressure of a carbon pile is shown in curve No. 1, Fig. 200. This curve is for vertical piles with pressure applied at the top, and the resistances observed and herein plotted for various pressures, include the effect of pressure due to the weight of the pile.

Consider a carbon pile or a group of them arranged as shown in Fig. 198. Assume that the reaction of the piles against the lever is similar to that of a perfectly elastic body. This assumption, while not strictly true, is sufficiently correct for purposes of computation. If the initial pressure due to the compression screws is 10 ounces on each pile, and an additional pressure of 10 ounces be impressed on one of the piles, 20 ounces must be added to the initial magnet pull, because the upward reaction of one pile *assists* the magnet pull, and as the magnet draws the lever down the effect of this reaction is lost and the equal force must be supplied. Therefore if 20 ounces be added to the magnet (or spring) pull, 10 ounces will be absorbed by compensating for the lost reaction of one pile, while 10 ounces will appear as compression of the other pile. After the magnet pull has passed the point where the reaction of the assisting pile disappears, any additional pull manifests itself entirely as compression of one of the piles. Thus, to compress one pile 5 ounces more than the initial compression requires an addition to the magnet pull of $5 + 5 = 10$ ounces if the initial pressure be 10 ounces but to compress to 30 ounces requires $30 + 10 = 40$ ounces increase in pull. Therefore for this particular case, up to 10 ounces additional compression requires an additional magnet pull of twice the compression desired, while above 10 ounces compression the additional magnet pull = (compression + 10) ounces. All this assumes that the lengths of the lever arms of adjusting screws, magnet and spring, are all identical. After final computations are made, the values found must be corrected for the actual lever arms.

R_2 is subject to change, increasing as R_1 decreases, up to the point where all the pressure is removed from R_2. For each value of R_1, the corresponding value of R_2 must be found from a curve similar to that shown by curve 1, Fig. 200, and the computations accordingly made.

Curve 2 in Fig. 200 is the variation of resistance R_2 with negative pull, *i.e.*, pull on R_1. When all external compression is removed from R_2, its resistance attains its maximum and there remains constant, as shown.

Since the relation between resistance and pressure of a carbon pile is hyperbolic, a general formula for resistance in terms of change in generator current would be cumbersome and difficult to use practically.

The size of the carbon plates is taken such that the current density is about 10 amperes per square inch of contact area, which fixes the surface dimensions.

There is an initial pressure on the carbon piles, due both to their weight and to the slight pressure of the adjusting screws. Referring to the curve 1, Fig. 200, the initial pressure on the top disc is taken as 10 ounces. Resistance of each pile is 22.5 ohms.

In order to reduce the loss through the piles there should be such a number in series as will produce a high resistance, or the connections should be made to points on the battery circuit where suitable potentials can be obtained which are lower than the line voltage, or a combination of both should be used.

In practice it has been found that the change in voltage across the booster or exciter field should be small, the maximum pressure across the field being limited to about 30 volts. The ratio between the field and armature windings must be such as to give the proper armature pressure when the watts, as predetermined from the characteristic, are impressed on the field.

It is customary to make only two computations for automatic boosters, namely, for the maximum voltage on charge, and the maximum on discharge, and that one showing the greater values of booster capacity and magnet pull is adopted. Usually the condition of minimum battery voltage and maximum discharge gives the greater values, and this will be the basis of the following calculations.

Take the general example given in the first portion of this chapter in which the booster was found to have a capacity of 80 K.W. and the exciter 200 watts. Plot curves of booster and exciter characteristics and from these calculate points for a curve of booster voltage for watts in the exciter field, as shown in Fig. 201. Note that the characteristics for exciter have watts as abscissæ. If no "overtravel" is provided for, the energy in the exciter field for the maximum of 118 booster volts (regulating) is found from the curve, Fig. 201, to be 12 watts.

Assume a magnet pull that is practicable with a normal current of 600 amperes. This will of course depend on the size of the core, the number of turns and general factors of design. Take for this case $P = 200$ ounces normal. For a 5 per cent degree of regulation the pull with maximum generator current will be $(1.05)^2 \times 200 = 220.5$ ounces, which is an increase of 20.5 ounces. If the mag-

net lever arm is 6 times that of the piles, the increase in pressure on the piles = 6 × 20.5 = 123 ounces. As there are 3 piles among which this pressure is divided, the increase in pressure per pile is $\frac{123}{3}$ = 41 ounces. Referring to the curves, Fig. 200, it is seen that

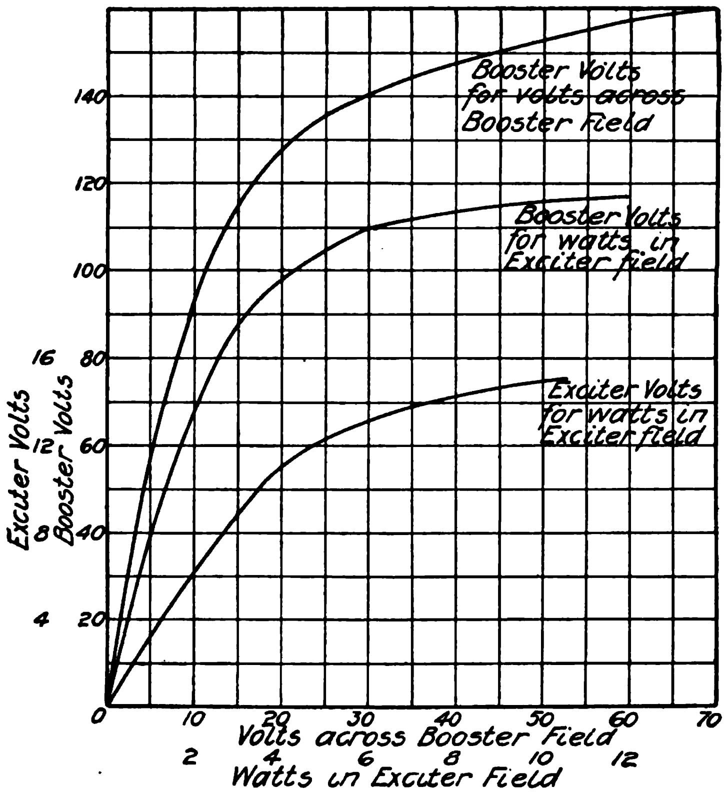


FIG. 201. Booster and Exciter Characteristics.

a pressure increase of 41 ounces reduces R_1 to 14 ohms per pile, or 42 ohms for the 3 piles; while R_2 is 42 ohms per pile, or 126 ohms total for the 3 piles.

The minimum voltage, ϵn, necessary to impress on a group of piles for maximum exciter field watts may now be determined from equation 140.

$$\epsilon n = \frac{\sqrt{4 \times 42 \times 12}}{1 - \frac{42}{126}} = \frac{\sqrt{2.016}}{0.666} = 66.6 \text{ volts.}$$

Since this voltage must exist at the time of maximum discharge and lowest state of battery charge, the volts per cell, ϵ, = 1.65. Therefore $n = \frac{66.6}{1.65} = 40.3$. Adopt 41 cells; $\epsilon n = 67.65$ volts. Voltage of ϵn, open circuit, $= 41 \times 2.1 = 86.1$ volts. Voltage across both groups of piles (open battery circuit) = 172.2 volts. Resistance of $R_1 + R_2$ when there is neither charge nor discharge of battery $= 6 \times 622.5 = 135$ ohms. Continuous current flow through $R_1 + R_2 = \frac{172.2}{135} = 1.275$ amperes. Continuous watts loss in controller $= 1.275 \times 172.2 = 219$ watts. Current in exciter field (from equation 139) is

$$c = \frac{67.65 \times (1 - 0.333)}{2 \times 42} \pm \sqrt{\frac{(67.65\,(1 - 0.333))^2}{(2 \times 42)^2} - \frac{12}{42}}$$

$$= 0.5365 \pm \sqrt{0.2874 - 0.2857} = 0.5365 \pm 0.00412$$

$$= \begin{Bmatrix} 0.54062 \\ 0.53238 \end{Bmatrix} \text{amperes.}$$

These two values for the current are so nearly identical that it is necessary to consider only one of them. Under certain conditions, however, the two current values may be greatly different, and the designer may select the one he considers preferable. Taking the field current as 0.54 ampere, the field resistance

$$r = \frac{\text{watts}}{(0.54)^2} = \frac{12}{0.292} = 41.1 \text{ ohms.}$$

$$i = \frac{\epsilon n}{R_2} = \frac{67.65}{126} = 0.536 \text{ ampere.}$$

Then $c + i = 1.076$ amperes, and drop through $R_1 = 42 \times 1.076 = 45.2$ volts. $v = 67.65 - 45.2 = 22.35$. This is also equal to $cr = 0.54 \times 41.1 = 22.2$, which checks closely enough for the many suppressed decimals in the computations.

The exciter field will be wound to take a maximum of 0.54 ampere and to have a resistance of 41.1 ohms. The ampere turns are to be such as to give an exciter armature pressure of 15 volts (see curves, Fig. 201). If the volts per ampere turn at that point of the characteristic are equal to .02, then the ampere turns $= \frac{15}{.02} = 750$. Number of turns $= \frac{750}{0.54} = 1385$.

Resistance per turn $= \frac{41.1}{1385} = 0.0297$ ohm.

Obviously, if either the normal magnet pull or the degree of regulation were increased, R_1 would be decreased for maximum magnet pull, and e_n would be correspondingly decreased. This would reduce the continuous energy loss through the two piles.

If "overtravel" be desired, the exciter watts and voltage must be increased proportionally, as described in the first portion of this chapter.

Fig. 202 shows a complete diagram of this booster system with separately driven exciter.

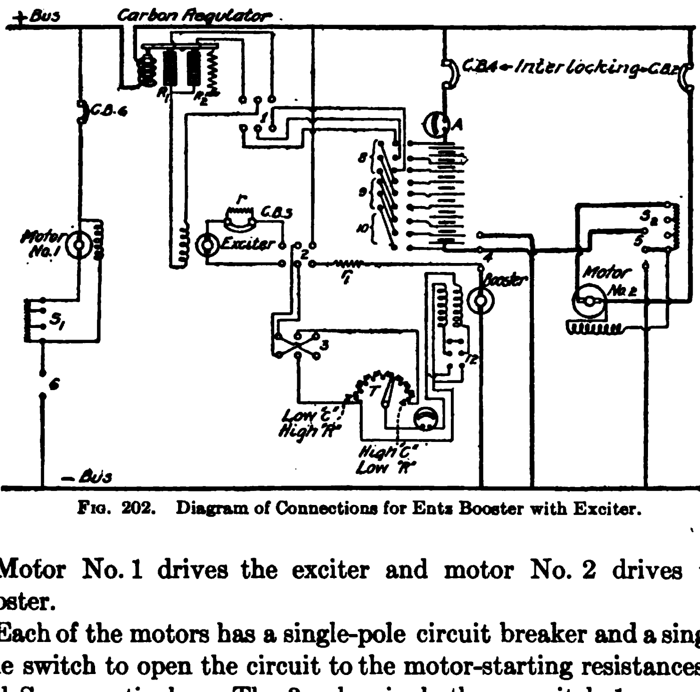


FIG. 202. Diagram of Connections for Entz Booster with Exciter.

Motor No. 1 drives the exciter and motor No. 2 drives the booster.

Each of the motors has a single-pole circuit breaker and a single-pole switch to open the circuit to the motor-starting resistances S_1 and S_2 respectively. The 3-pole, single-throw switch 1 connects the regulator and exciter field to the section of battery used for excitation. From the exciter armature, the booster field current passes through a single-pole circuit breaker, CB3, to switch 2. A resistance r is shunted across the circuit breaker terminals, its resistance being proportioned to admit the passage of the maximum regulating booster field current. Therefore, if CB3 opens, the current to the booster field is not interrupted but simply limited to a safe value. By means of switch 2 the booster field may

be connected to the exciter armature by throwing to the left. By throwing switch 2 to the right, the booster field is connected directly to the bus bars through a fixed resistance r_1, switch 3, rheostat T and switch 12. With its field connected to the bus bars, the booster is operated as a plain shunt machine for charging or discharging, switch 3 being for the purpose of reversing the booster field as may be desired. The field current may be hand-controlled by T, as is obvious. As shown, the booster field is divided into two (or more) sections which may be connected in series or parallel, the series connection being used when working directly on the bus bars, and the parallel when the field is connected to the exciter. Switch 12 is to make this change in connection, the field coils being in series when the switch is thrown on the upper contacts, and in parallel when the switch is thrown downwards. By means of switch 4, the battery may be connected to the bus bars through the booster armature when the blade is thrown on the lower clip, or it may be connected directly across the bus bars, cutting the booster entirely out of circuit when the blade is thrown to the upper clip. Switches 8, 9 and 10 are triple-pole, double-throw switches for shifting the connections of the regulator and exciter field to different sections of the battery. Any battery section across which the regulator is connected, suffers a small but constant discharge, and therefore, in a short time becomes further exhausted than the other portions of the battery. In order to equalize this regulator discharge the arrangement shown has been devised.

If all the switches be thrown to the right, that section of the battery, indicated at the upper end, will supply current to the regulator and exciter field through switch 8. If switch 8 should be thrown to the left, the second section of the battery will be put in circuit, through switches 8 and 9, the first section being cut out. If now switch 9 be thrown to the left, the third section will supply the regulator and exciter field through switches 8, 9 and 10. Thus the switches at the beginning are all thrown to the right, and as the battery sections are changed the switches are successively thrown to the left. When the lower end is reached, the procedure is reversed, the switches are successively thrown to the left from the bottom section up to the top. In this way the regulator and exciter fields are easily shifted to different battery sections and the regulator discharge equalized over the entire battery.

*The Lyndon Externally Controlled Booster.**

This form is shown diagrammatically in Fig. 203. The general principle is the same as that before described, namely, the inverse variation of two resistances between which one terminal of the field is connected, while the other field terminal is connected to a point on the battery lying halfway between the points to which the free terminals of the resistances are connected. The methods

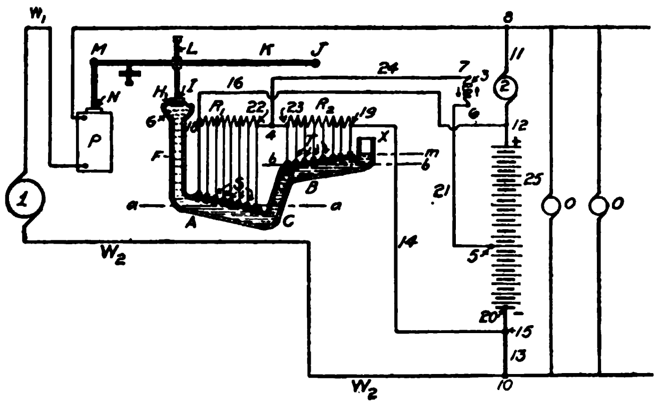


FIG. 203. Lyndon Externally Controlled Booster.

of computation of sizes and voltages of booster, exciter and driving motor, and the volts to be impressed on the booster or exciter field, are all as given in the first portion of this chapter.

The controller is shown in detail in Fig. 204 and consists of two small flat boxes A and B, made of cast iron, glass or any material not attacked by mercury, and placed so that one is at a higher elevation than the other, both being set at an acute angle with the horizontal. The two boxes are connected by a vertical tube C which leads from the lower end of the lower box to the lower end of the upper one.

A second vertical tube is connected to the upper end of the lower box, and at the upper end of this second tube is placed a flexible diaphragm H, similar to the kind used on steam-actuated damper regulators.

The tops of the flat boxes are of ebonite or some similar solid insulating material. These tops are fastened to the boxes with screws, a soft rubber gasket being placed between the box edges and

* Serial No. 514,120.

the cover, so that a liquid-tight joint is formed. Contact points, made of polished steel, pass through the box covers, being spaced as shown in Fig. 205a. These contact points are very small bolts, placed with their heads on the inner surface of the cover and

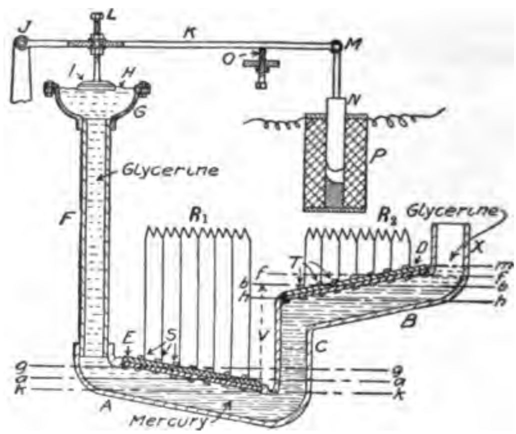


FIG. 204. Lyndon Booster Controller, Detail of Controller.

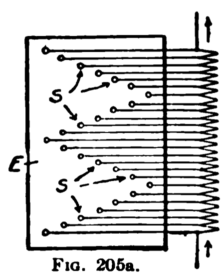


FIG. 205a.

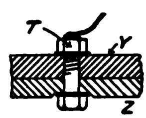


FIG. 205b.

Arrangement of Contacts, Lyndon Booster Controller.

the threaded end on the outside. A sheet of soft rubber is interposed between the head of the contacts and the cover, so that when the nuts are screwed up on the outside the heads press into the soft rubber and form liquid-tight joints as indicated in Fig. 205b. Since the tops of the boxes are inclined, the contact points are arranged in stepped relation. To the outer ends of the contact bolts are attached terminals leading to two resistances, R_1 and R_2, there being one resistance for each box.

A magnet having its winding in series relation with the generator current, acts to pull down a lever which presses on the dia-

phragm. Any magnet pull, therefore, gives a coresponding pressure on the diaphragm.

Mercury and glycerine are poured into the boxes and connecting tubes until they are filled and the respective levels of the two liquids are as indicated in Fig. 204. Under these conditions there is a head of mercury acting in one direction and a head of glycerine acting to oppose it. The net unbalanced force, then, is that due to the mercury head minus that due to the glycerine.

A one-inch head of mercury = 0.5 lb. pressure per sq. in.

A one-inch head of glycerine = 0.035 lb. pressure per sq. in.

Net unbalanced force = $(0.5\,a - 0.035\,b)$ lbs. per square inch, in which a and b are the heights of the mercury and glycerine columns respectively. This force acts against the diaphragm and is opposed by the pull of the magnet, the two being equal when normal generator current passes through the magnet winding.

If the ampere turns of the magnet be varied, its pressure (through the lever) against the diaphragm will be greater or less than that due to the static head of the mercury, and movement of the diaphragm and the bodies of glycerine and mercury will result, the glycerine acting both as a liquid piston to move the mercury and as a spark-suppressing medium. As the mercury diminishes in one vessel and increases in the other, the contact points in the cover of the one are no longer electrically connected through the body of mercury, while in the other vessel more points are electrically connected. Therefore, the two resistances which are joined to the contact points are short-circuited to a greater or less extent by any movement of the mercury.

Referring to Fig. 203, the operation of a system using this control is indicated. 1 is the main generator, the current from which passes to the battery and the external load O, O through magnet winding P. The battery is connected across the line through booster armature 2. Resistances R_1 and R_2 have numerous steps connected to the contact pins in the covers of the vessels A and B. One terminal of R_1 is connected to the positive side of the battery and one terminal of R_2 to the negative side, the other terminals of R_1 and R_2 being joined together. The booster field winding 3 is connected on one side to the middle point of the battery and on the other side to the junction of R_1 and R_2.

If the system be adjusted for a certain normal generator output, the current passing through the magnet winding produces

a pull that just balances the force due to the opposing head of mercury, and, if the external load is also equal to the normal generator output, the mercury will stand at a level in both boxes such that one-half of R_1 and one-half of R_2 are each short-circuited.

The potential drop from 12 to 15 is equal to the potential of the battery, and the drop from 12 to 5 is one-half the battery potential. Therefore, with this condition, point 5 and point 4 are at the same potential and no current passes through the booster field; the booster voltage is zero, and there is neither charge to, nor discharge from, the battery.

If the load increases, a greater current tends to flow from the generator, and the pull of the magnet P is increased, the magnet core moves downward depressing the diaphragm and forcing mercury out of A into B, thereby increasing the resistance of R_1 and decreasing that of R_2. The drop through R_1 becomes greater than that through R_2, and point 5 is at a lower potential than that of point 4. Current flows from 12 through R_1 to 4 and through the booster field 3, to 5, its magnitude depending on the ratio of R_2 to R_1. This current through the field produces a booster voltage in a direction to assist the battery to discharge and take up the load in excess of the normal generator output. Conversely, if the external load should decrease, the generator current will tend to decrease, and the flow through P being reduced, the pressure due to the static head of mercury will be greater than the pull exerted by the magnet. Consequently mercury will pass out of B into A and thereby decrease the resistance of R_1 and increase that of R_2. This changes the potential of point 5 and makes it more nearly equal to that of the negative side of the battery. Current will therefore flow through booster field 3 from 6 to 7, or in a direction opposite to that in which it flowed in the previous case. This sets up a voltage in the booster armature in a direction to charge the battery, and the current in excess of that necessary for the load passes into the battery.

For each external load change there is a certain booster voltage necessary to cause the proper charge or discharge, and by having a number of contact points in each vessel cover, many voltage gradations up or down from zero may be obtained.

One of the principal features of the system is the small change in the pressure head of mercury with complete short-circuiting or open-circuiting of either of the resistances, so that the opposing

forces of mercury head and magnet pull do not vary greatly throughout the range of motion of the device. Also, the dash-pot action of the liquids makes it self-damping.

With this controller, currents up to 5 amperes may be passed through the contacts, so that an exciter does not become necessary until the size of the booster is such that the exciting energy exceeds 600 watts maximum on regulation. Also, the voltage across which the resistances are connected may be taken at any value desired, as it is only a question of proportioning the resistances and the number of contact points to work under the voltage chosen. This booster controller will here be treated fully because it is an example of the general case of booster controllers having high resistance and which can be connected either across the battery or the line as may be desired.

In practice, a portion of the generator current is shunted around the magnet winding, and the generator load is adjusted for any desired value by varying the current through the shunt.

For a given percentage of regulation, the contact boxes must have a certain slope, so that with movement of the mercury a change in head is produced that is proportional to the increase or decrease in magnet pull due to the increase or decrease in generator current. There is another factor that affects the slope of the boxes, and that is the change in the pull of the magnet due to the change in the position of the magnet core and consequent change in the reluctance of the magnetic circuit. The core of the magnet has considerable travel with corresponding variation in the air gap.

By properly shaping the cores, that is, making them more or less pointed or rounded on the end, magnets can be produced that will give a substantially constant pull with constant excitation over a considerable range of motion. Unless controller magnets are so designed there will be no stability of position, nor is regulation possible, for with any change either of excitation or opposing force, the core will move to its extreme position up or down, owing to the rapidity of increase or decrease in pull with change in the position of the core. The change in pull due to change in core position with constant excitation should be not greater than 7 per cent between the highest and lowest points, or 3½ per cent from the middle or neutral position to lowest or highest position.

The resistance from one contact point to the next and consequently the voltage change from point to point is not constant. It

has been found that as the booster field is decreased from full excitation towards zero, the motion of the mercury is so rapid that it opens the circuits from point to point faster than the self-induction of the fields is able to follow. Consequently, the real break in the field current is not from point to point consecutively but from the starting point to one several points removed. With the stored energy in a fully charged field dissipated in the break over only one or two points, sparking will occur.

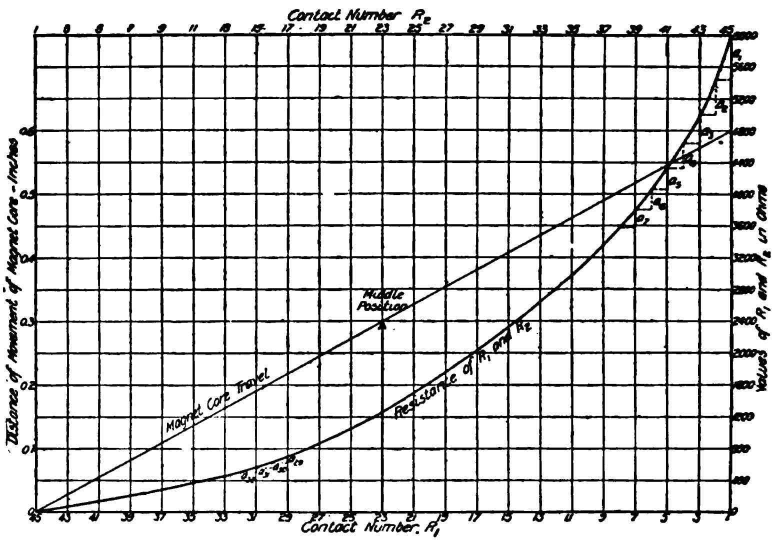


FIG. 206. Curve of Division of Resistance among Contact Points for Booster Controller.

To prevent this, the resistance between adjacent points decreases progressively from the first point to the last, the first point being that one at the highest position of the box cover and the last point being at the lowest position. When the first point touches the mercury the entire resistance is short-circuited and the maximum booster field excitation is produced, and between points 1 and 2 the maximum resistance is inserted, while contact between the last point only and the mercury means the whole resistance is in circuit and the current through it is a minimum. Therefore between the last point and the one adjacent thereto the minimum resistance section is connected.

Fig. 206 shows a curve that indicates the rate of change in the

resistance from point to point. This curve was found experimentally. It closely approximates, however, the division of resistance such that the watts in the circuit opened at any point are constant. The abscissæ are for both R_1 and R_2.

Also, the movement of a magnet core to produce corresponding change in the number of contacts immersed is plotted, the total travel of the core being here assumed as 0.6 inch. The dotted lines forming steps on the under side of the curve indicate the resistance from point to point, each of the vertical dotted lines a_1, a_2, a_3, a_4, etc., representing, to scale, the amount of resistance between the two points between which the vertical line is taken. The movement of the magnet is indicated by the ordinates to the left.

The computations of sizes of booster, motor, exciter and general equations are as have been given in the first portion of this chapter.

For producing a voltage high enough to overcharge the battery the booster field is connected directly to the line through a rheostat, as in the case of the Entz booster.

Consider a booster of 80 K.W. capacity having an exciter; such machines have the characteristics shown in Fig. 201. The exciter field energy required for the highest booster regulating voltage is 12 watts.

The regulator resistances should be high, to keep down the continuous loss through them. These can be made any desired value. Assume that the total resistance for each set of contacts is 6000 ohms, and divided among the contact points in accordance with the curve, Fig. 206.

In the middle position $R_1 = R_2 = 1280$ ohms. Then $R_1 + R_2 = 2560$ ohms.

If the normal battery voltage be 550 volts and the floating voltage of the battery be 2.1 volts per cell, it will consist of 262 cells.

First Case. Resistances connected across battery, exciter field connected to the middle cell.

$$\text{Number of cells across each resistance} = \frac{262}{2} = 131.$$

Voltage across each resistance at normal load, battery floating, $= 131 \times 2.1 = 275$ volts.

$$\text{Continuous loss} = \frac{275}{1280} = 0.215 \text{ ampere} = 0.215 \times 275 = 59 \text{ watts.}$$

Voltage across each resistance when battery is nearly exhausted

and discharging maximum current = 131 × 1.65 = 216 volts. It is better to design the controller so that the maximum booster voltage will be produced without the magnet having to travel to its extreme lower (or upper) position, leaving some margin for adjustment and "overtravel." Assume in this case that contact point 30 of R_1 is the proper position of the controller for delivering 12 watts to the exciter field.

From equation 140,

$$\text{watts} = w = \frac{(\epsilon n)^2\left(1 - \frac{R_1}{R_2}\right)^2}{4\,R_1}.$$

For controller point 30, $R_1 = 640$, $R_2 = 2220$, $4\,R_1 = 2560$, $\epsilon n = 216$, $(\epsilon n)^2 = 46{,}656$, $1 - \frac{R_1}{R_2} = 0.709$, $\left(1 - \frac{R_1}{R_2}\right)^2 = 0.5027$.

$$\text{Then } w = \frac{46656 \times 0.5027}{2560} = 9.1 \text{ watts.}$$

This number is less than the required 12 watts; therefore the controller must travel further than point 30 for maximum regulation.

Try point 32. $R_1 = 520$, $R_2 = 2480$.

Solving for w, this is found to be 13.98 watts, which is greater than the 12 watts required. Point 32 will therefore be adopted as the limiting point for regulation.

Current in exciter field, from equation 138, is

$$c = \frac{216\left(1 - \frac{520}{2480}\right)}{2 \times 520} \pm \sqrt{\left(\frac{216\left(1 - \frac{520}{2480}\right)}{2 \times 520}\right)^2 - \frac{12}{520}}$$

$$= 0.1641 \pm \sqrt{(0.1641)^2 - .02309}$$

$$= 0.1641 \pm .0616 = \begin{cases} 0.2257 \text{ ampere} \\ 0.1025 \text{ ampere} \end{cases}$$

there being two values of current which satisfy the conditions.

Resistance of field will be

$$r = \begin{cases} \dfrac{12}{(0.2257)^2} = 235.7 \text{ ohms} \\[2ex] \dfrac{12}{(0.1025)^2} = 1142 \text{ ohms} \end{cases}$$

Whichever is best suited to the type of machine under consideration may be adopted. Assume that 0.2257 ampere and 235.7 ohms will be the values used.

$$\text{Current through } R_2 = i = \frac{216}{2480} = 0.087 \text{ ampere.}$$

Drop through $R_1 = 520\,(0.2257 + 0.087) = 162.6$ volts.
Volts across exciter field $= 235.7 \times 0.2257 = 53.17$.

The sum of the volts drop through R_1 and the volts across the exciter field must be equal to ϵn. In this case the sum $= 162.7 + 53.17 = 215.87$, or, practically, 216 volts.

If the field were connected directly across one half of the battery, *i.e.*, all points immersed in the mercury, and when the pressure per cell is 2 volts, the maximum current flow would be $\frac{2 \times 131}{235.6}$ $= 1.11$ amperes.

When the regulator magnet is in its middle position and the battery on charge, the maximum flow will be, $\frac{2.7 \times 131}{1280} =$ 0.276 ampere. The resistance, therefore, should be designed to carry 1.11 amperes from point 45 to point 44, gradually diminishing from point 44 to point 23, at which latter point the carrying capacity must be 0.276 ampere, this value being constant from point 23 to point 1.

If the regulator be worked to the last contact point, that is, to where $R_1 = 20$ ohms and $R_2 = 5440$ ohms, the maximum watts that may be supplied are, from equation 140,

$$w = \frac{(\epsilon n)^2\left(1 - \frac{R_1}{R_2}\right)^2}{4\,R_1} = \frac{(216)^2\left(1 - \frac{20}{5440}\right)^2}{4 \times 20} = 578.8 \text{ watts,}$$

and the current would be

$$c = \frac{216\left(1 - \frac{20}{5440}\right)}{2 \times 20} \pm \sqrt{\left(\frac{216 \times \left(1 - \frac{20}{5440}\right)}{2 \times 20}\right)^2 - \frac{578.8}{20}}$$
$$= 5.38 \text{ amps.}$$

$$\text{Resistance of field for 566.5 watts} = \frac{566.5}{(5.38)^2} = 20 \text{ ohms.}$$

If a booster, having a field that takes this much energy, were put across the regulator, the current-carrying capacity of R_1 and R_2 would have to be $\frac{131 \times 2}{20} = 13.1$ amperes between points 45 and 44, diminishing to 0.276 ampere at point 23, the resistances from point 23 to point 1 all having a carrying capacity of 0.276 ampere.

If desired, the carrying capacities between points 45 and 23 may be diminished below the figures given, as they have to carry these maximum currents only momentarily. The capacity from point 45 to point 44 may be made to carry the maximum current for 40 seconds only, this decrease being reduced between each succeeding pair of points until between points 22 and 23 there can be no reduction below the maximum current as computed above. If the field of the exciter selected, gives a proper exciter armature voltage with the given current through it, but has a resistance lower than desired, a dead resistance having a current-carrying capacity equal to that of the field may be inserted in series with the field. The value of this resistance is of course the necessary resistance as computed, minus the resistance of the field winding.

Second Case. Resistances connected across line with exciter field terminal connected to the point in the battery determined by equation 145.

$n = 0.248\ E = 0.248 \times 550 = 136.4$, or 136 cells from end of battery, opposite booster connection. Continuous loss practically same as in first case, *viz.*, 59 watts.

When battery is nearly exhausted and discharging maximum current, the voltage across R_2 is $e_2 = 136 \times 1.65 = 224.4$ volts, and voltage across R_1 is $e_1 = 550 - 224.4 = 325.6$ volts.

Try, in this case, the contact point No. 30 as the limiting motion of the regulator for a 12-watt field.

From equation 150

$$w = \frac{\left(550 - 224.4\left(1 + \frac{640}{2200}\right)\right)^2}{4 \times 640} = 26.4 \text{ watts.}$$

Therefore contact point No. 30 is well within the limit of operation.

Taking point 30 with its values of R_1 and R_2, the current in the exciter field winding, from equation 149, is

$$c = \frac{\left(550 - 224.4\left(1 + \frac{640}{2200}\right)\right)}{2 \times 640} \pm \sqrt{\left(\frac{550 - 224.4\left(1 + \frac{640}{2200}\right)}{2 \times 640}\right)^2 - \frac{12}{640}}$$

$$= 0.20336 \pm 0.15033 = \begin{Bmatrix} 0.35369 \\ 0.05303 \end{Bmatrix} \text{ampere.}$$

Either value may be adopted.

Resistance of the field

$$r = \frac{w}{c^2} = \begin{Bmatrix} \frac{12}{(0.35369)^2} = 95.9 \text{ ohms} \\ \frac{12}{(0.05303)^2} = 4277 \quad `` \end{Bmatrix},$$

the resistance adopted depending on which of the two currents is taken for the design of the exciter.

If the field were at any time connected directly across the cells with only one division of the regulator resistance in circuit, the maximum current flow would be $\frac{325}{95.9 + 20} = 2.8$ amperes, 20 ohms being the resistance of the single division. The regulator resistance should have a carrying capacity of 40 per cent of this maximum current or, $0.40 \times 2.8 = 1.12$ amperes, between points 45 and 44, gradually diminishing to 0.276 ampere at point 23.

Maximum watts that can be delivered by the regulator working to the last contact point is

$$w = \frac{\left(550 - 224.4\left(1 + \frac{20}{5440}\right)\right)^2}{4 \times 20} = 1262 \text{ watts.}$$

The slope of the boxes is determined as follows: If H = normal head of mercury in inches, the pressure per square inch on the diaphragm is proportional to it. The opposing pull of the magnet is proportional to the square of the current in the coil. The head of glycerine must be deducted from that of the mercury, that is, the net head is $(H - h)$, h being the head of glycerine taken as the equivalent of a certain number of inches of mercury. Also, if the magnet core moves from its middle position, the pull will be that due both to increase in current and changed position of the magnet core.

If the core were moved to its extreme position without change in the current through the coil, its pull P in pounds would be

$= P + gP$, g being the percentage increase in pull for maximum movement of the magnet core. Therefore the pull to be added to the normal magnet pull is less by the amount gP than would be necessary if there were no change in magnet pull due to change in position of the core. Hence

$$I^2 : P :: (I + \phi I)^2 : P - gP + p, \qquad (160)$$

p being the pull, in excess of P, necessary to compensate for change in head, and ϕ being the percentage increase in generator current for regulation.

For P the value of $(H - h)$ may be substituted, the magnet pull being equal to the net pressure head.

Then $$I^2 : (H - h) :: (I + \phi I)^2 : (H - h) - g\,(H - h) + S, \qquad (161)$$

S being the equivalent of p in terms of mercury head.

Whence; $$(H - h)\,(I + \phi I)^2 = I^2\,(H - h - g\,(H - h) + S),$$

$$S = (H - h)\,(2\phi + \phi^2 + g), \qquad (162)$$

which is the value of the total change in head for movement of the core from the mid position to extreme low position. Since the total change in head is twice the change in the level of the mercury in either vessel, being the sum of the changes in level in the two vessels, the vertical distance from the middle point to the upper point $= \frac{S}{2}$, and the vertical distance between extreme upper and lower points $= S$.

The magnet pull necessary depends on the head of mercury, the volumetric contents of one vessel, and the travel of the magnet core. When the core is in its highest position all the mercury is in one vessel; movement to its lowest position sends all the mercury into the other one.

If a = volumetric contents of one vessel, in cubic inches, and J = average pull or pressure due to head $(H - h)$, then the work for a complete movement of the core $= aJ$ inch pounds. If t= travel of magnet core in inches, the normal magnet pull $= \frac{aJ}{t}$. (163)

Since the degree of regulation is fixed partially by the slope of the boxes and not by the normal magnet pull only, the head H may be made as small as desired, compatible with quick working, thus keeping P within reasonable limits.

As an example, consider a controller to regulate the load on a system, in which the normal generator current is 600 amperes,

maximum output, number of cells, battery and generator voltages all as given in the general example at the beginning of this chapter; R_1, R_2 each 6000 ohms, maximum exciter field resistance 235.6 ohms, field current for maximum booster output 0.2257 ampere, as in the example just preceding. Assume $\phi = .04$, *i.e.*, a regulation of 4 per cent, and that the change in the magnet pull due to change in position $= g = 3$ per cent, in moving from its middle position to either extreme position. Take the pounds pressure per square inch per inch head of mercury as 0.5 and the pounds pressure per square inch per inch head of mercury $= 0.035$.

The head of mercury required to produce a pressure equal to a one-inch head of glycerine is $\frac{0.035}{0.5} = 0.07$ inch.

Take the mercury head in normal position as 4 inches and the glycerine head as 6 inches.

Glycerine head in terms of mercury head $= h = 6 \times .07 = 0.42$ inch.

Then from equation 162

$$S = (4 - 0.42)\ (2 \times .04 + (.04)^2 + .03) = 0.3985 \text{ inch.}$$

The magnet pull will be based on a total movement of the core = 0.6 inch, and the volumetric contents of each box which is 1.7 cubic inches. This latter quantity is determined from the design of the device, depending on the area of the cover necessary to carry the requisite number of contact points. The depth of the boxes is about $\frac{3}{8}$ inch. Hence cover area $\times \frac{3}{8}$ inch = volumetric contents. Normal head $= 4 - 0.42 = 3.58$ inches $= 1.79$ lbs. pressure per square inch, the pressure of mercury being (approx.) 0.5 lb. per inch head. Inch-pounds $= 1.79 \times 1.7 = 3.043$ inch-lbs. required to move mercury from lower to upper vessel.

$$\text{Pull} = \frac{3.043}{0.6} = 5.07 \text{ lbs.} = 81.1 \text{ ounces.} \quad \text{(Equation 163.)}$$

Pull for maximum head

$$= \frac{(4 + 0.3985 - 0.42) \times 0.5 \times 1.7}{0.6} = 5.635 \text{ lbs.}$$

Of this, 3% of 5.07 lbs., or 0.1521 lb., is due to change in position of the magnet core, leaving 5.4829 lbs. due to the flow of current through the coil. Since 600 amperes produces a pull of 5.07 lbs., the following proportion results:

$$600 : \sqrt{5.07} :: x : \sqrt{5.483},$$

in which x = maximum generator current.

$$x = \left(\sqrt{\frac{5.483}{507}}\right) \times 600 = 624 \text{ amperes},$$

or an increase of 4 per cent in the generator current for complete movement of the magnet core and mercury from middle position to the extreme downward position.

For the so-called "constant current" or non-reversible booster, only one resistance is used and is connected as shown in Fig. 207. The maximum booster voltage is produced when all the resistance

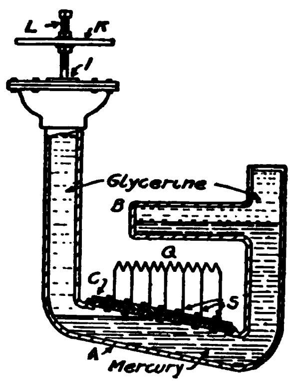


FIG. 207. Lyndon Booster Control for Non-Reversible Booster.

is cut out of the field, *i.e.*, R_1 = zero. The minimum voltage is that produced when all, or nearly all, the resistance is in circuit with the field. In this case, however, the downward movement of the magnet produced by increase in external load increases the value of R_1, so that the booster voltage falls with augmentation of load. Chapter XXXII gives fully the conditions under which non-reversible boosters work, and the application of an external controller to meet these conditions is simple and will be obvious to the student. The small change in head with maximum movement of the mercury is maintained by placing the flat vessel at the upper end of the tube as shown. The mercury forced into this spreads itself over a considerable area and therefore changes its depth, and consequently its head, very little.

Bijur Booster.

The principles of the Bijur booster controller are similar to those of the Lyndon controller just described. In the former controller the contact points are moved to the mercury; in the latter the mercury is moved to the points.

This arrangement is illustrated diagrammatically in Fig. 208.

G is the generator and C a magnet in series with the generator circuit having a moving core K which pulls the end of lever D downwards. The opposite end of D is fastened to a rock shaft F, which rotates through a small angle when the pull of the magnet and the opposing pull of spring S are unequal. S has one end

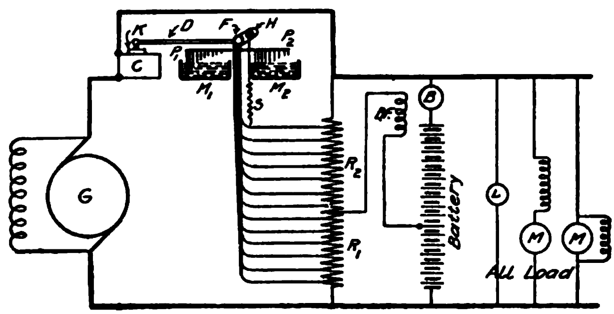


FIG. 208. Diagram of Connections of Bijur Booster.

fastened to a short lever H that is fixed on the rock shaft at an angle with the axis of the spring. The angle that it makes with the axis of the spring is such that the increase or decrease in spring tension, due to movement of H, is compensated for by a corresponding reduction or increase in the lever arm to produce a torque on the rock shaft, so that the product of spring tension multiplied by lever arm to produce turning is a constant, and the spring will produce a constant turning moment on the rock shaft. Attached to the rock shaft are the two insulating bars P_1, P_2, on opposite sides of the shaft. Contact points are arranged in stepped relation as shown, each group being placed just over a vessel of mercury, the two vessels being indicated by M_1, M_2.

The contact points, which are made of polished steel, are connected to divisions of resistances R_1 and R_2. The booster field is connected between the middle point of the battery and the junction of R_1 and R_2.

Obviously, if the pull of the magnet is greater than the resisting

torque of the spring (with due allowance for the lever arms of spring and magnet), the rock shaft will be rotated slightly in a counter-clockwise direction, and this will lift some of the points P_2 out of the mercury, and immerse more of the points P_1 in the mercury. This reduces R_1 and increases R_2, with the result that a booster voltage is produced to cause discharge.

If the load is reduced, the turning moment due to the magnet pull is less than that produced by the spring, and the rock shaft is rotated in the opposite direction with the converse result.

The standard magnet windings are designed for 100 amperes normal current. If the normal generator output exceeds this, a shunt is placed round the magnet winding, which shunt is so proportioned as to take all the normal current in excess of 100 amperes up to 500 amperes. If the generator current exceeds 500 amperes, a horseshoe magnet placed over a bus bar is used.

Screw stops are provided which may be adjusted to limit the movement of the lever D in either or both directions, thereby limiting the booster voltage and preventing the charge or discharge of the battery at injurious rates.

A feature of the Bijur regulator is that with a given current flow through the magnet, the magnet and spring turning effects will be equal and balance each other in any position within the range of motion of the instrument. Theoretically, the regulation is not a certain percentage of the generator output, depending on the value of the external load, but the change in generator current is a constant for any external load change, the increase or decrease in magnet pull being just enough to overcome the friction of the instrument. After starting to move, motion will continue until a battery charge or discharge is produced that brings the generator load exactly to its normal value. In practice, however, the controller "overtravels," taking for an instant a greater change in current than is necessary to overcome friction, and when a certain point is reached, begins to "retreat" and continues to return towards its normal position until the point is reached where the booster voltage has just the value needed to bring the generator current to its constant value. This "overtravel" gives a quick booster action, as has before been explained, and improves the regulation.

Fig. 209 shows the front and Fig. 210 the rear views of one of these regulators with one set of contacts only, and used to con-

trol a non-reversible booster. The mercury vessel and contact points are clearly seen in Fig. 209. The connecting wires that lead from the points to the resistances are bunched together and form a cable, which passes through a hole in the switchboard panel

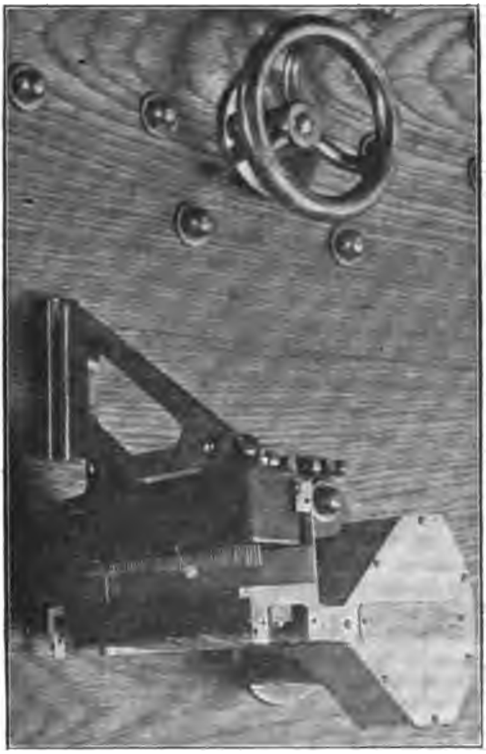


FIG. 209. Bijur Regulator for Non Reversible Booster, Front View.

just above the rock shaft. The segmental-shaped cap forms a cover for the end of the rock shaft and the bend in the cable. The hand wheel shown in Fig. 209 is for the purpose of adjusting the spring tension, so that the generator current can be adjusted to any desired value by changing the amount of force opposing the magnet pull.

In the rear view, Fig. 210, the rock shaft, cable, magnet, levers and other parts are seen. The rock shaft is mounted in a ball-bearing journal to reduce the friction. The pull of the magnet is about

4.5 lbs. and is made constant through a range of 0.75 inch, by rounding the end of the core. The spring has its lower end hooked in an arm of a bell crank. The hand wheel in front has a threaded hole in its hub into which a stud, connected with the other arm of the bell crank, is screwed. By turning the hand

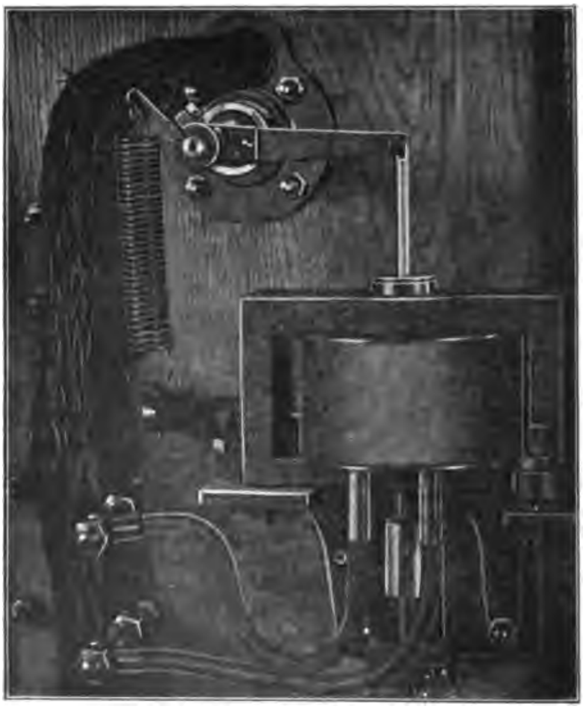


Fig. 210. Bijur Regulator for Non-Reversible Booster, Rear View.

wheel, the stud moves inward or outward, thereby changing the position of the bell crank arms and therefore the tension of the spring.

The division of resistances among points is as has been given in the immediately preceding description of the Lyndon controller. The analysis is also identical, except that the computation of slope and mercury head as opposing forces disappear in the Bijur controller the spring tension taking their place.

Since the spring tension is constant,

$$DP = SH, \tag{164}$$

P being the magnet pull, D its lever arm and SH being the product of spring pull by its lever arm at any time.

$$P = \frac{SH}{D}. \tag{165}$$

The value of P is fixed by the friction of the moving parts and is principally due to the twisting effect that must be exerted on the flexible cable. If this is s ounces at the magnet for complete travel of the regulator,

$$(P + s) = \frac{sH}{D} + F, \tag{166}$$

F being the friction moment of the controller taken at the end of the magnet lever.

The increase in current for any discharge will be

$$(I)^2 : (I + \phi I)^2 :: P : P + s, \tag{167}$$

whence

$$s = 2\phi + \phi^2. \tag{168}$$

If it is desired that the increase in generator current shall not exceed 4 per cent of the normal, and 6 ounces pull at the end of the magnet lever are required to overcome the friction of the device plus the resistance to bending of the cable, also that the magnet lever arm, D, is 5 inches, then

$s = 2\phi + \phi^2 = 2 \times .04 + (.04)^2 = 0.0816 = 8.16$ per cent of the normal pull.

Since $8.16\% = 6$ ounces,

Normal pull, $P = 73.5$ ounces,

$PD = SH = 73.5 \times 5 = 367.5$ ounce-inches.

In taking the lever arm through which the spring acts, its value is the perpendicular distance from axis of spring to center of rock shaft and not the length of the spring lever, unless it is set at right angles to the spring axis.

The double resistance regulator for reversible boosters is shown in Fig. 211. This is mounted entirely on the back of the switchboard, the whole device being constructed on an iron back plate which is attached to the switchboard panel by means of four bolts.

The rock shaft C carries on it three levers. One, not visible in the picture, is connected to tension rod H, another lever G has one end of the retracting spring S attached to it by a short link as shown. The lower end of the spring is hooked into a link which is fastened to one arm of a bell crank, the other bell crank arm B being con-

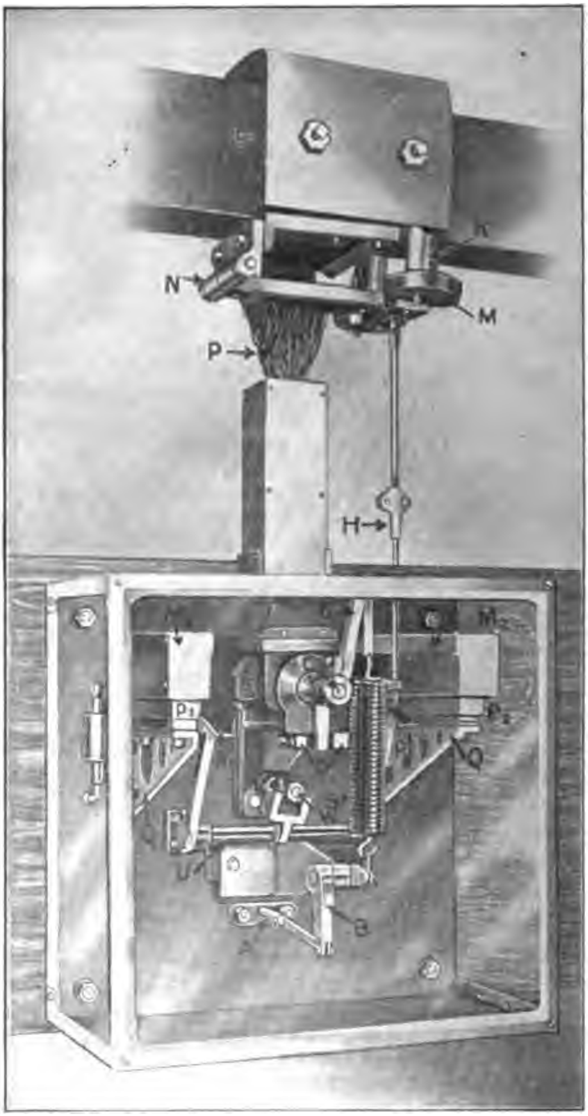


Fig. 211. Bijur Regulator for Reversible Booster.

nected by a link to the threaded stud A, which passes through the panel. On the front side of the board, a hand wheel having a threaded hub works on this stud, and by turning the wheel it is obvious that the tension on the spring may be varied. The third lever Y, is an aluminum frame which is fixed on the rock shaft, extending an equal distance on either side of it, and on each end is placed the series of stepped contacts, by means of which the resistances R_1 and R_2 are varied. These contacts are covered with aluminum covers M_1 and M_2, which covers fit over the mercury vessels P_1 and P_2 respectively. These vessels are carried on brackets Q, as shown.

A small arm projects vertically downward from the rock shaft, and works between the adjustable stops *d*, by means of which the range of motion of the regulator, and consequently the battery current, is limited.

The arms carrying the flat springs R, R, are for the purpose of preventing oscillations of the instrument when starting its operation. These arms are fastened to the auxiliary rock shaft U, which, in turn, is moved by a yoke working on the stud W. Stud W passes through the panel and has a hand wheel fastened to its front end. Movement of this hand wheel will cause the arms to swing inwards towards the panel, pressing the springs R, R, under the edges of covers M_1, M_2, and this holds the regulator in its middle position. After adjusting the booster and battery on the circuit and making ready, the springs are withdrawn by the hand wheel, and the regulator begins operation. In starting the booster, however, and connecting the battery to the line, sudden rushes of current will make the regulator jump from full short-circuiting of one resistance to full short-circuiting of the other, causing current rushes that may throw open the station circuit breakers. This occurrence is prevented by the use of the stop springs R, R.

The regulating magnet is a special form for bus bar mounting. It consists of a shoe L of wrought iron which surrounds the bus bar on two sides and the top, being open at the bottom. The portion on the bottom of the bus bar, screwed to the shoe, is made of brass, so that the shoe is magnetically discontinuous around the bus bar. From the lower right-hand corners of the shoe, project two cylindrical studs K, which are rounded at the end. Over these studs moves a piece of iron, M, shaped somewhat like a figure 8, the

studs projecting into the holes in M; M is held in position and guided in its motion by the hinge joint N, to which it is connected by the lever hinged at N and bolted to M. The parts forming the hinge and lever are of brass, so that they do not offer a path for any of the magnetic lines that pass from one side of the shoe to the other. Therefore, practically all the lines that are set up by the passage of electric current through the bus bar pass from one stud across the air gap to M, from M through the second air gap to the other stud, thus producing a magnetic pull tending to draw the piece M further on to the studs. A tension rod H attached to the rock-shaft lever, has its lower end fastened to M, and the magnet pull is, therefore, opposed by the spring tension.

The movement of the magnet armature M is limited by means of an upper and a lower nut threaded on a stud, which stud passes through a hole in the armature lever. The set screws having jam nuts, shown on the side of the magnet shoe, are for the purpose of holding the magnet securely in position, the set screws taking hold against the side of the bus bar.

Fig. 212 shows a complete diagram of connections of the Bijur system. The numbers at either end of the resistances 7 and 8 indicate the positions of the first and 45th contact points. Fuse 29 is shunted by a resistance 13, which will admit the passage of only sufficient current to give maximum exciter field excitation, the fuse acting as a protection against accidental short-circuits. The booster and exciter are driven by separate motors. 25 is a 3-pole, single-throw knife switch, which, when closed, connects the regulating resistances to the main circuit and the exciter field to the middle point of the battery. 17 is a circuit-breaker in the line from exciter to booster field. It is shunted by a resistance 12, and the arrangement protects the circuit without the possibility of interrupting the operation of the booster.

The ampere meter 5 shows the booster field current. When switch 26 is closed, and the 3-pole, double-throw switch 27 is thrown to the left, the booster field is connected to the exciter for automatic regulation, the booster field windings being connected in parallel. For hand control on charge or discharge, switch 26 is opened and switch 27 closed to the right. This connects the booster field windings in series and, by throwing switch 28 to the left, current is conducted directly from the main circuit to the field wind-

ings, passing through rheostat 9, the direction of current flow being such as to produce a booster charging voltage. If switch 28 be thrown to the right the direction of current through the field is reversed, and the booster voltage is in a direction to cause discharge.

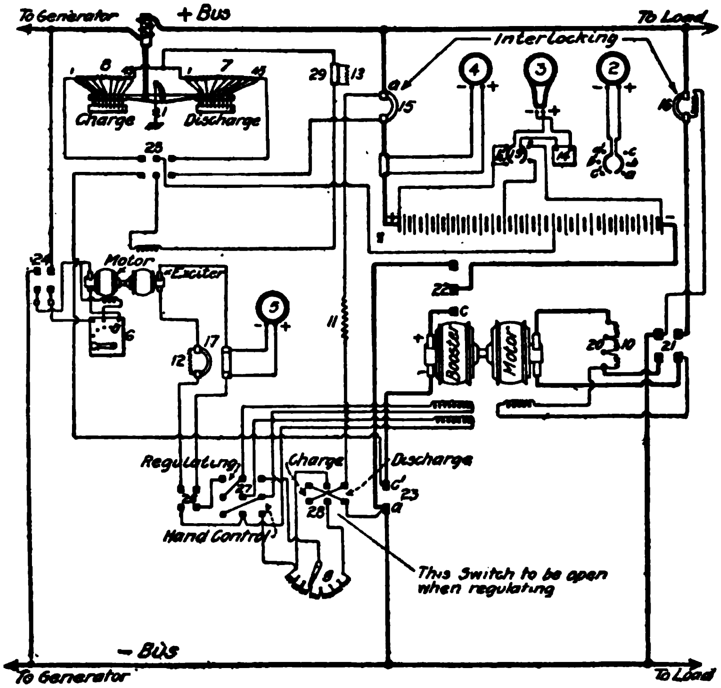


FIG. 212. Bijur Booster System.

It is to be noted that the wires from the main circuit to the booster fields are connected outside of all circuit breakers, so that if the main circuits open, the booster excitation is not destroyed. Circuit breakers 15 and 16 are made interlocking, so that if either opens the other one will also. This arrangement prevents the booster from being connected in circuit when the motor circuit is open. The single-pole, double-throw switch 22 connects the booster in circuit when thrown downwards, and switch 23 is closed. When switch 23 is open and 22 is thrown upwards, the battery is connected direct to the line, the booster being out of the circuit.

Ampere meter 4 is a two-way reading instrument, and indicates the charge or discharge current. The voltmeter 2 is to show the

voltages of the main circuit, the battery, and the booster. The wires to the voltmeter switch points are not shown on the diagram, but points *a*, *a′* are connected to correspondingly lettered points in the main circuit at circuit breaker 15 and switch 23 respectively; points *b*, *b′* are connected to the terminals *b*, *b′* on the switch 19, which is a voltmeter switch for the recording voltmeter. These terminals *b*, *b′* are connected to the opposite ends of the battery;

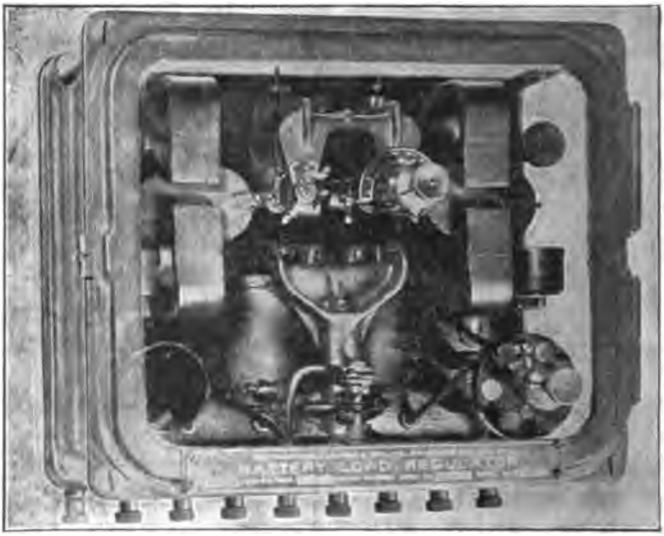


Fig. 213. Westinghouse Booster Controller.

points *c*, *c′* are connected to correspondingly lettered points at switches 23 and 22.

Westinghouse Booster.

Another form of automatic booster regulator is the Westinghouse. This is a relaying device for controlling the booster field.

Fig. 213 shows the regulator and Fig. 214 is a diagram of the parts and connections, showing its operation.

The generating system is connected to the left-hand end of the bus bars, while the load is connected to the right-hand end. The battery in series with the booster is placed across the bus bars between the load and the generator as shown. Between the generator and the battery is an ordinary meter shunt. Connected to

this shunt and in series with a variable resistance, are the controlling wires of the regulator.

These wires are connected to a movable coil B on the end of an arm, which is free to move about pivot T, the coil working

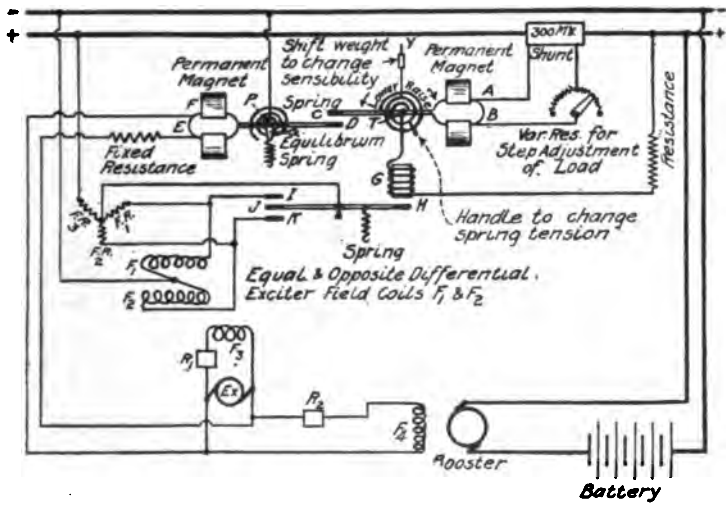


FIG. 214. Westinghouse Booster Controller; Diagram of Connections.

between the pole faces of permanent magnet A. This part of the apparatus corresponds to the mechanism of an ordinary indicating type of ammeter. Opposing the movement of this coil is a spiral spring. On one end of the arm supporting the movable coil B is a contact C. This makes a connection with another contact D on a similar moving arm, which latter carries on its opposite end coil E, which is connected across the brushes of an exciter dynamo *Ex*, the amount of current flowing through the coil being proportional to the exciter voltage. Coil E is placed between the pole faces of a permanent magnet F, so that a pull is produced when current passes through it.

The arm carrying D and E is pivoted at P, and has a spiral spring attached to it, which opposes the pull of the coil E. Also it has a downwardly projecting piece Q, just below the pivot P, to the end of which an equilibrium, coil spring is attached. This spring is so set that for zero voltage of the exciter the coil and arm will assume a horizontal position, the axis of the projecting piece Q coinciding with the axis of the spring. Obviously any movement

of the lever in either direction from the horizontal will increase the tension on the equilibrium spring.

When contact is made between C and D, the auxiliary circuit through magnet winding G is closed, energizing the solenoid G of the main relay. This attracts the armature H of the relay, overcoming the pull of the opposing spring, and contact is made between J and K. With the contact at C and D broken, the spring attached to H draws it down, making contact between J and I.

In series with each of the two equal and opposite fields, F-1 and F-2 of the exciter is a fixed resistance FR-1 and FR-2 respectively. The circuit energizing these fields may be from any convenient source of direct current, a preventive resistance FR-3 being placed in series with the source of supply. The amount of this resistance depends upon the voltage of the supply circuit.

When the contact J is in its middle position, touching neither I nor K, an equal amount of current will flow through the fixed resistances FR-1 and FR-2 and the corresponding field coils F-1 and F-3, and since these coils are wound oppositely, their magnetic effects neutralize and zero voltage will be produced at the exciter armature.

If contact is made between J and I, shunting the fixed resistance FR-1, more current will then flow through the field coil F-1 than through the field coil F-2, so that the exciter will build up its voltage in the direction determined by the field coil F-1. When the exciter begins to build up its voltage in this direction, the shunt field coil F-3 will begin to act, and will continue to build up until the exciter reaches maximum voltage unless prevented. If current in the field coil F-1 is reduced, the voltage of the exciter will be reduced, the current flowing through the exciter shunt coil will be diminished and the exciter will tend to demagnetize, its voltage returning to zero.

As the exciter voltage increases in value, the pull produced by the coil E increases proportionally, so that it tends to move above or below the horizontal, depending upon the direction in which the current is flowing in the coil, which is determined by the polarity of the exciter. The torque of the coil E is opposed by the equilibrium spring, so that for any given voltage of the exciter the contact D occupies a certain position above or below the horizontal.

A vertical arm Y is attached to the lever CB at right angles to it and projecting upwards, just above the pivot about which

the lever moves. This arm carries an adjustable weight, which may be shifted vertically so that the coil B may be made to take any position within its range for a given current flowing through the coil, which current is proportional to that through the line shunt; or it may be so adjusted that the torque required to move the coil B will be changed, and therefore the current through the shunt to produce movement of B will likewise be changed.

The operation of the apparatus is as follows:

If a constant load of 400 amperes is to be maintained on the generating circuit, a current of this value passing through the shunt will hold the coil B in a horizontal position. Coil E will also be in a horizontal position, the exciter voltage will be zero, and the battery voltage will be exactly equal to that of the line at point of connection thereto. Current will neither enter nor flow out of the battery, which will be floating on the line. If load increases to 600 amperes, an increased current will then flow through the shunt and thereby increase the current through the coil B. This will produce a torque overcoming the spring tension and closing the contacts at C and D. The moment contact is made at C and D the armature H will be attracted by solenoid G making contact at J and K. This will cause field winding F-2 to preponderate over the field winding F-1, which will tend to increase the exciter voltage, and which in turn, assisted by the shunt field, will aid in increasing the voltage. This will send a current through booster field winding FA and produce a booster voltage to cause the battery to discharge until the current passing through the shunt drops slightly below 400 amperes. This reduction, aided by the torque in the coil E, due to the high booster voltage, will break contact at C and D. The moment contact is broken at C and D, the spring will cause contact to be made at J and K. This will cause the field F-1 to preponderate over the field F-2 and will tend to reduce the booster voltage. The resultant action is that contact will be very rapidly made and broken between C and D, and therefore between J and K and I, so as to maintain a mean booster voltage to produce charge or discharge within very close limits of the desired value.

In case it is desired to change the average load carried by the generator, this may be done within fixed limits by changing the tension of the spiral spring on lever CB, a handle being provided for the purpose of increasing or decreasing the tension.

If a greater change of load is desired than this spring adjust-

ment can give, the variable resistance in series with coil B is changed through as many steps as necessary, which varies the current through B for a given current through the shunt.

The action of this regulator is independent of the drop in voltage of the battery due to continued discharge, and it will maintain a constant load on the generator, up to the voltage capacity of the booster to cause the required discharge or charge.

With this regulator, the same instrument can be used for any size installation, since the current consumed at the contacts is exceedingly small, and the effect on voltage, due to the two equal and opposite fields, would be only a fraction of that produced by the shunt field F-3 in the exciter. This means, then, that these two equal and opposite fields simply serve as pilot fields to determine the polarity of the booster voltage.

The analysis of this system differs from that of all the others herein described in that the ampere meter relay works on a given change in current strength through the shunt, and the percentage change in generator output is the same for any external load change or condition of the battery.

Let

at = ampere-turns required for exciter fields at time of maximum booster voltage.

g = percentage of the exciter field ampere-turns supplied by the pilot field.

$(1 - g)\,at$ = ampere-turns in exciter shunt field.

t = no. of turns on each pilot field.

T = no. of turns on shunt field.

c = amperes in pilot field when either resistance is short-circuited.

Since one field is always in opposition to the other, the current through the active field must be equal to that required for excitation plus that in the counter field. Call the opposing current i. From the characteristics of the exciter and the booster, the net ampere-turns necessary to produce g per cent of the total ampere-turns in the exciter field when the maximum booster voltage is induced = atg, at being the total ampere-turns necessary to produce full excitation of the exciter when booster delivers maximum voltage on regulation. Since c and i pass through the same number of field-turns, the net ampere-turns of the pilot field are

$$atg = t\,(c - i). \qquad (169)$$

If e = volts across either pilot field when the resistance in series with it is short-circuited, and E = volts across the line

$$R_3 (c + i) = E - e,$$

whence
$$R_3 = \frac{E - e}{c + i}. \tag{170}$$

Also, when one field is active and the other, counter to it, is taking current through the resistance in series therewith, the voltage impressed across field and resistance being e,

$$i = \frac{e}{R_1 + r}; \quad R_1 = \frac{e}{i} - r, \tag{171}$$

R_1 being the value of the resistance and r that of the field.

Also for the active field,

$$c = \frac{e}{r} \quad \text{and} \quad rc = e. \tag{172}$$

Loss through resistances and pilot fields when regulator is in normal position is

$$W = Ei_1 \tag{173}$$

in which i_1 is the current to resistance R_3 and the two pilot fields.

Since the two pilot fields have equal resistances, and $R_1 = R_2$, the resistance of the circuit when neither resistance is short-circuited is

$$R_3 + \frac{R_1 + r}{2};$$

therefore,

$$i_1 = \frac{E}{R_3 + \frac{R_1 + r}{2}}. \tag{174}$$

The shunt field winding on the exciter is to give $(1 - g)\,at$ ampere-turns. If the maximum exciter voltage = v, then resistance *per turn* is

$$\psi = \frac{v}{(1 - g)\,at}. \tag{175}$$

The number of turns, T, is determined from the efficiency fixed on. If the exciting energy due to the shunt field is to be f per cent of the exciter output, then total resistance of field is

$$R_r = \frac{v}{fI}, \tag{176}$$

in which I = maximum current delivered by the exciter. Hence

$$T = \frac{\frac{v}{fI}}{\frac{v}{(1-g)\,at}} = \frac{(1-g)\,at}{fI}, \qquad (177)$$

the size of the wire being such as to give a resistance of $\frac{v}{(1-g)at}$ per turn.

As an example, assume an exciter which for maximum output is to have a field excitation of 4000 ampere turns = at. The pilot field is to supply 30 per cent of the total, = g. The voltage across either exciter pilot field when its resistance is short-circuited to be 50 volts, = e.

The line voltage, 550, = E.

Exciter voltage with 4000 ampere-turns in the field = 100 volts.

Current through one pilot field and resistance when other pilot field resistance is short-circuited, taken at 0.05 ampere, = i.
Number of turns on each pilot field = 6000 = t.

Then the net ampere-turns for pilot fields = 0.30 × 4000 = 1200 ampere-turns. From equation 169, 6000 (c − 0.05) = 1200, whence

$$c = 0.25 \text{ ampere.} \qquad r = \frac{50}{0.25} = 200 \text{ ohms.}$$

$$R_s = \frac{550 - 50}{0.25 + 0.05} = 1666.6 \text{ ohms; (equation 170).}$$

$$R_1 = \frac{50}{0.05} - 200 = 800 \text{ ohms; (equation 171).}$$

The continuous loss through resistances and pilot fields when the regulator is in normal position is

$$i_1 = \frac{550}{1666.6 + \frac{800 + 200}{2}} = 0.2574 \text{ ampere; (equation 174).}$$

Loss = 550 × 0.2574 = 141.6 watts.

Watts in pilot fields (maximum), = 50 (0.25 + 0.05) = 15 watts.

The high loss is due to the voltage of the line being far greater than required for the voltage applied across the exciter pilot fields.

If the voltage of the source of supply were 50 volts, and R_3 removed, the loss would be

$$i_1 = \frac{50}{\frac{800 + 200}{2}} = 0.1 \text{ ampere.}$$

Loss = 50 × .10 = .5 watts.

Therefore if the resistance R_3 be removed, and the pilot field current be taken from a group of $\frac{50}{1.65} = 30$ cells, the system would be improved in efficiency. The total ampere-turns on the exciter



FIG. 215. Westinghouse Booster, Exciter and Motor.

field are 4000, of which 1 − 0.30 = 70 per cent are to be furnished by the shunt winding.

70% of 4000 = 2800. $v = 100$.

$$\text{Resistance per turn} = \frac{100}{2800} = 0.0357 \text{ ohm.}$$

If per cent of output for shunt field excitation is to be 5% and maximum current = 12 amperes,

$$\text{Resistance total of shunt field} = \frac{100}{.05 \times 12} = 166.6 \text{ ohms.}$$

$$T = \frac{2800}{.05 \times 12} = 4666 \text{ turns.}$$

Fig. 215 shows a booster set with exciter adapted to be controlled by the device just described. This picture is typical of sets of this kind for regulation by external control. The tendency is, however, to use two separate motors, one to drive the booster and one for the exciter, and thus divide the set into two parts, as has been mentioned before.

NOTE: Since this chapter was written, the Westinghouse and General Storage Battery companies have been absorbed by the Electric Storage Battery Company, and the Westinghouse and Bijur Booster systems are now owned by that company.

CHAPTER XXXV.

CURRENT SUPPLY FOR BOOSTER MOTORS.

In the discussions of various booster systems which have been given, it has been assumed that the battery output on discharge, at any time, is equal to the difference between the generator current and the current delivered to the line, while the battery input has been taken as generator current minus the line current. Expressed mathematically the assumption is: Battery current = $I_x - I_0$, I_x being total line current and I_0 the generator current. When $I_x = 0$, battery current $= - I_0$, which signifies that the battery current is equal to that from the generator, and the discharge is negative, or charge takes place.

This assumption is incorrect in that it does not include the current required to drive the booster motor, and all computations heretofore given must be corrected for this additional load. This factor was neglected in the discussions of boosters in order to simplify the theories of the various types described.

Reversible Booster.

The energy to the booster motor to cover the continuous free running losses, that is, when the booster voltage is zero, and the motor and booster armatures are running, appears as an addition to the average load on the generator and should be added to I_0 to obtain its true value. This will usually approximate 10 per cent of the motor capacity plus 3 per cent of the booster capacity, depending on the efficiencies of the machines. When I_x differs from I_0 and current goes either into or out of the battery, there is a load imposed on the motor which must be furnished by current from the battery, which current is additional to that supplied by the battery to the external load. The true value of I_x, then, is the sum of external load plus booster motor load.

If V = booster voltage at any time,

F = battery amperes to external load = $(I_x - I_0)$,

E_c = Line or motor voltage,

p_1 = efficiency of booster,

p_2 = efficiency of motor,
I_B = battery current to motor,
Booster load = V × total battery current.

On discharge,

Total battery current = $F + I_B$.

Hence

$$\text{Booster load} = V\,(F + I_B). \tag{178}$$

$$\text{Motor energy input} = \frac{V\,(F + I_B)}{p_1 \times p_2}. \tag{179}$$

$$\text{Motor amperes} = I_B = \frac{V\,(F + I_B)}{E_0 \times p_1 \times p_2}. \tag{180}$$

Putting $E_0 \times p_1 \times p_2 = Z$,

$$ZI_B = V\,(F + I_B). \tag{181}$$

Whence

$$I_B = \frac{VF}{Z - V}. \tag{182}$$

On charge,

$$\text{Total battery current} = F - I_B \text{ and } I_B = \frac{VF}{Z + V}. \tag{183}$$

These equations are used to compute I_B for extreme condition of battery charge or discharge, where V is known. However, V depends for its value on the battery current, and the more general formula is found by substituting for V in equation 181 its value, which, for discharge, is the battery resistance multiplied by the total battery current, or

$$V = R\,(I_B + F).$$

The equation becomes

$$I_BZ = R\,(I_B + F)^2.$$

Solving for I_B,

$$I_B = \frac{Z}{2R} - F \pm \sqrt{\left(\frac{Z}{2R} - F\right)^2 - F^2} \tag{184}$$

This equation apparently gives two values of I_B. The greater value is not, however, a practicable one in booster work, and the negative sign before the radical should be used to compute the motor current.

$$\text{For charge,} \quad I_B = \frac{Z}{2R} + F - \sqrt{\left(\frac{Z}{2R} + F\right)^2 - F^2}. \tag{185}$$

As an example of the correction to be made in booster computations, take the general example given in the first portion of the previous chapter in which $I_0 = 600$ amperes. If an increase of 5 per cent in generator current is allowed on maximum load,

$$I_0 = 630 \text{ amperes.} \quad I_{X\,MAX} = 1800 \text{ amperes.}$$

The battery current to the line for $I_{X\,MAX}$ is $1800 - 630 = 1170$. For minimum battery voltage of 1.65 volts per cell on discharge the booster voltage = 118 volts. If the line voltage = 550 and the efficiency of booster and motor on full load are each 90 per cent, then $Z = 550 \times .90 \times .90 = 445.5$.

From equation 182, motor current is

$$I_B = \frac{118 \times 1170}{445.5 - 118} = 421.5 \text{ amperes.}$$

The actual maximum station output then is $1800 + 421.5 = 2221.5$ amperes, and the battery discharge is $1170 + 421.5 = 1591.5$ amperes. This means that the current-carrying capacity of the booster must be increased in the ratio of 1170 to 1591.5 and the size of the battery must be such as to give a discharge of 1600 amperes without falling below 1.65 volts per cell. This is, of course, an extreme condition, but one that may often be reached. This is a point that should never be neglected, as its omission will inevitably lead to the installation of a battery too small for the intended service. Instances have been known where the battery has been so much too small that an increase in external load would cause the booster to discharge, but the current discharged was just about enough to supply the motor, so that the industrious regulating efforts of battery, motor and booster had no effect on the external load and the fluctuations it caused on the generating apparatus. This failure to regulate is usually accompanied by low efficiency of booster and motor.

If the battery is fairly well charged and the internal resistance, R, has a normal value of say .025, the motor current for an output to line of 1500 amperes will be, from equation 184,

$$I_B = \frac{445.5}{2 \times 0.025} - (1500 - 600) - \sqrt{\left(\frac{445.5}{2 \times 0.025} - 900\right)^2 - 900^2}$$
$$= 51 \text{ amperes.}$$

Total battery discharge = 951 amperes instead of 900.

The increase in generator current with a good regulating booster

will be so small in this case as to be negligible. Therefore the generator output is taken at its normal value of 600 amperes.

Non-reversible Booster.

In the case of the non-reversible booster there is no increase, but, on the contrary, a decrease in motor current with increase in external load. This is due to the diminution in booster voltage at the time of discharge.

The booster energy at normal external load is I_0V, in which V = booster voltage, being usually about 0.15 N. Since the generator must supply all the energy under normal conditions, the normal generator current is

$$I_G = I_0 + \frac{I_0V}{Z} = I_0\left(1 + \frac{V}{Z}\right). \tag{187}$$

For increase in external load, if ϕ = percentage regulation,

$$I_G(1 + \phi) = I_0(1 + \phi)\left(1 + \frac{V}{Z}\right), \tag{188}$$

which is the total generator current on discharge. The current taken by the motor on discharge is

$$I_G(1 + \phi)\frac{V_1}{Z}, \tag{189}$$

V_1 being the booster voltage for discharge.

Current to line from generator = total generator current minus current to motor, or

$$I_{LG} = I_G(1 + \phi) - I_G(1 + \phi)\left(\frac{V_1}{Z}\right). \tag{190}$$

Current to line from battery = $I_x - I_{LG}$. (191)

For condition of $I_x < I_0$, and charge taking place, total generator current is

$$I_G(1 - \phi) = I_0(1 - \phi)\left(1 + \frac{V}{Z}\right), \tag{192}$$

and current to battery is total generator current minus current to motor, and to external load, or

$$I_{BG} = I_G(1 - \phi) - I_G(1 - \phi)\frac{V_2}{Z} - I_x, \tag{193}$$

in which V_2 = booster voltage on charge.

Example: A 110-volt system having an average load on external circuit of 100 amperes, maximum load 300 amperes, minimum load 10 amperes:

Minimum battery voltage 112 volts when cells are at 1.75 volts each. $N = \frac{112}{1.75} = 64$ cells. Maximum regulating battery voltage at 2.3 volts per cell $= 64 \times 2.3 = 147$ volts.

Range of voltage through which power bus bars work $= 147 - 112 = 35$ volts.

Normal booster voltage $= \frac{35}{2} = 17.5$ volts $= V$.

$V_1 = 112 - 110 = 2$ volts and $V_2 = 147 - 110 = 37$ volts.

Take combined efficiency of booster and motor at 76 per cent. Then $Z = 110 \times 0.76 = 83.6$.

Normal generator current $I_G = 100\left(1 + \frac{17.5}{83.6}\right) = 120.9$ amperes (equation 187).

Take $\phi = 5$ per cent.

For maximum external load = 300 amperes the generator current, I_{LG}, to line is

$$120.9 \times 1.05 - 120.9 \times 1.05 \times \frac{2}{83.6} = 123.5 \text{ amperes.}$$

Current from battery $= 300 - 123.5 = 176.5$ amperes, which is its maximum discharge rate for this condition.

For charge, generator current $= 100\,(0.95)\,(1.209) = 114.8$ amperes.

Current to battery, taking I_x as its minimum value of 10, is $114.8 - 114.8 \times \frac{37}{83.6} - 10 = 54.1$ amperes.

If the battery is fairly well charged, it will receive maximum charge and deliver maximum discharge with less change in booster voltage than the extreme values given above, in which case both the charge and discharge rates will be higher, the motor taking less current on charge and more on discharge than under extreme conditions.

To find the maxima, substitute the proper values of V_1 and V_2 in the equations. V will remain unchanged. $V_1 = E_A - \epsilon N$, and $V_2 = \epsilon N - E_A$, ϵ being the volts per cell for any condition and E_A = normal battery voltage.

CHAPTER XXXVI.

THE DESIGN AND SELECTION OF BOOSTERS.

THE character of booster best suited to the conditions under which it is to work depends on

(1) Average load.
(2) Maximum load.
(3) Minimum load.
(4) Character of service.
(5) Change in the average load throughout the day.
(6) Changes in the average load with season of the year.

The booster must be designed to take care of the maximum battery discharge for any period during the year.

In systems on which the maximum demand is great but fluctuating, and the average demand small, the non-reversible booster is most suitable, if a reduction in line voltage at time of heaviest load is allowable, as it carries only the average current.

Where the average demand is large, and the maximum is not very much greater than the average, one of the types of booster which is in series with the battery should be used.

In general, separately excited or externally controlled boosters are the lowest in cost and give the best regulation.

Where the average demand changes frequently during the day, as in electric railway and office building plants, the system must be capable of being easily and quickly adjusted to meet the changed load demand. Where the booster motor is subjected to considerable variation in the supply voltage it should be designed to work below the "knee" of the magnetization curve, so that an increase or decrease of voltage at the armature is attended by a corresponding decrease or increase in field excitation, otherwise the speed of the motor will vary and the boosters and regulators will tend to "hunt." The resulting current oscillations may throw open the circuit breakers at a time when even a momentary interruption of service would be an annoyance. This condition may occasionally happen in rolling mills by reason of drop in steam pressure on the

boilers due to sudden heavy demand for steam at the roll engines, resulting in a momentarily lower speed of the generator engines.

Automatic boosters must be wound on frames which are made of good quality of steel or soft iron if reasonable regulation is desired. Fields and poles having high remanence will make a sluggish booster. The reason for this is evident when the hysteresis factor is considered. Refer to Fig. 216, which is a hysteresis loop. Starting from the point zero, the booster voltage will rise with the load. When the maximum is reached and the external load falls off, reducing to the normal, and giving zero excitation there is still a voltage

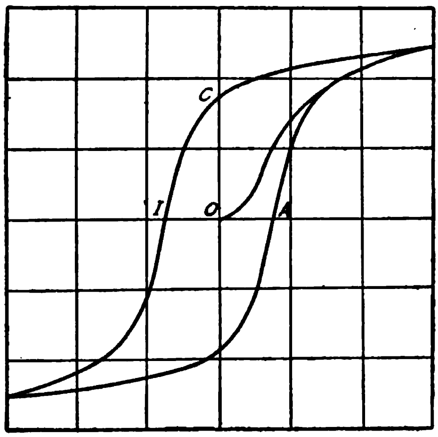


FIG. 216. Hysteresis Curve.

tending to discharge, since there is magnetization equal to OC left in the fields which is generating a discharging E.M.F. The booster voltage does not drop to zero until the load has fallen off below the normal, and with a reverse excitation from O to I the battery is still discharging, though the load be less than normal. When the maximum on the opposite side is reached, and the load begins to increase, the reverse action takes place. When the load rises again to normal, battery charge still continues, and from O to A the battery is charging, though the load is in excess of the normal. This trouble does not affect non-reversing boosters, which always work well up above zero of the magnetization curve. The foregoing applies only to those boosters which reverse, their magnetization continually passing through zero.

While the voltage proceeding from this remanence is very small, it must remembered that at normal voltage of battery and line

and normal load a very small booster voltage will cause a heavy charge or discharge.

Boosters having laminated field poles respond more quickly to voltage changes than will those with solid poles, and should be so constructed unless a system of control having considerable overtravel is used. With overtravel, *i.e.*, an initial application to the booster field winding of a voltage in excess of that required for regulation, solid field poles can be forced to respond quickly to changes in the field excitation.

As has been previously mentioned, boosters must frequently pass currents of great magnitude when the booster voltage is low, particularly in the case of non-reversible or "constant-current" boosters. It therefore is advisable to use commutating poles or a compensating winding of the Ryan type on the field frame. The size of a reversible, regulating booster is fixed by only two factors, namely, the space to accommodate field windings that will produce the required maximum armature voltage, and the ability to commutate the maximum current through the armature. The question of heating under load is not a factor, because the heavy loads are only of momentary duration. To keep down the size of the booster and yet have it commutate heavy currents at low voltages, it is necessary to use interpoles or a compensating winding. Boosters of these types are in service which regulate on loads that require the frequent passage through them of currents five or six times as great as the normal continuous capacity of the machine. In case such form of machine is used, its normal capacity may be only 20 or 25 per cent of the maximum current flow through it, instead of the 40 per cent assumed in the preceding discussions. A further advantage of machines having commutating windings is the abnormally small field energy required for excitation. As is well understood by designers of direct-current dynamo-electric machinery, a long air gap is necessary to prevent the distortion of the magnetic field by armature reaction and consequent sparking at the commutator, and the energy for excitation is proportional to the length of the air gap. Obviously, if the machine be provided with some auxiliary device whereby armature reaction is neutralized, the length of the air gap may be reduced so that it is only great enough for mechanical clearance, and the exciting energy will be correspondingly diminished.

Many boosters of this type are in operation which require one-

half of one per cent of their output or less for field excitation. This applies to machines of 50 K.W. capacity and above.

This means not only that the constant losses in the booster are less than in the ordinary form of machine, but, that much larger boosters may have their fields directly controlled from an automatic regulator without interposing an exciter, thereby eliminating an additional machine with its driving motor, switches and connections, and the losses and time lag due to it.

With regulators that will deliver 400 watts, an 80-K.W. booster can be regulated directly from the regulator, and if this capacity be 25 per cent of the maximum output, it means that the booster has a regulating capacity of 320 K.W.

The most efficient form of regulator is one using a bus bar shoe as a magnet, as there is practically no energy loss, while in a magnet winding or a shunt carrying heavy currents there may be an appreciable I^2R loss.

All energy used in auxiliary apparatus is lost, except in the case of the booster itself, where most of the energy of the motor is given back to the system. Therefore the auxiliaries must be designed to absorb as little energy as possible; heavy shunts and continuously working motors should be avoided excepting of course the booster and exciter motors.

Whether a single unit of motor, booster and exciter is preferable to driving the booster with one motor and the exciter with a separate motor, depends on conditions; usually the two separate units are cheaper and more efficient. When the exciter is mounted on the shaft with the booster, it must run at a very low speed for a machine with a small output. This is illustrated in the general example given in the first part of Chapter XXXIV. An 80-K.W. booster requires an exciter of 1200 watts capacity on the basis of 1.5 per cent of the booster output for excitation. If a compensated winding booster were used taking 0.5 per cent, the exciter output would be 400 watts. If either of these exciters be run at the speed of an 80-K.W. machine, instead of the speed suitable for very small machines, a much larger frame would be required for them, increasing the cost, the energy for their excitation and the continuous losses.

Since boosters usually carry heavy currents at low voltages, the commutator and brush surfaces necessary are often much larger than in the case of standard dynamos. In order to make use of

standard commutator segments to keep the length of the brush holders down to standard and keep the commutator speed within the limits of good practice, double commutators are sometimes used. These are placed one on either side of the armature, and are connected in parallel or series, as required.

This arrangement permits of a reduction in the size of the booster for the reason that the maximum voltage is usually fixed by the battery voltage when it is being "boiled" or overcharged. On overcharge, however, only a small current is desired, so, on such occasions the two commutators may be connected in series and a

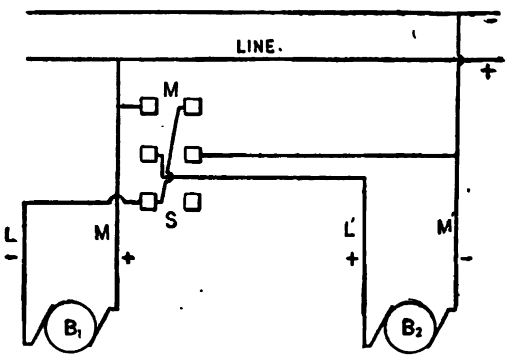


FIG. 217. Switch to Connect Commutators in Series or Parallel.

lower voltage — and consequently smaller — booster may serve. In addition to the reduction in size of the booster which is affected by the double commutator machine, the efficiency is markedly increased. The efficiency of a booster which works under widely varying loads would be very small if it were not for the fact that the voltage of the machine also varies, and the efficiency is very similar at different loads to that of a series wound dynamo. Since the principal losses in small machines of this type are the iron losses, it is desirable to make them as small as possible, which is effected by the double winding and commutators.

The leads from the brushes are carried to a double-pole, double-throw switch, which when thrown upwards connects the two commutators in parallel and when thrown downwards connects them in series.

This arrangement is shown in Fig 217. B_1 and B_2 are the booster commutators, M is the switch, one terminal being blank. The connections are obvious from the diagram.

CHAPTER XXXVII.

COMPOUNDING BOOSTER-CONTROLLED POWER PLANTS.

ALL the booster systems described in the preceding chapters are designed either to maintain the bus bar voltage constant or allow it to diminish with increase in external load.

In railway systems and plants of a like character it is desirable to have the voltage increase with increase in load. This requires a special arrangement with boosters and batteries, as the function of the battery is to maintain a constant load on the generator.

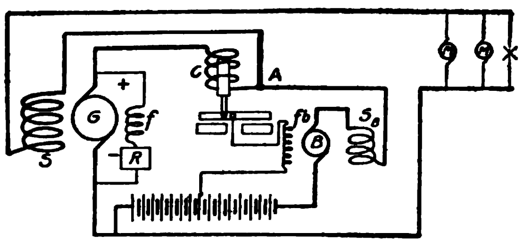


FIG. 218. Connections for Compounding Generator and Booster.

The method of arranging for voltage increase with load is as indicated in Fig. 218. G is the generator armature, having the shunt field f, and a series field S. C is the controller magnet winding in series with the generator current. B is the booster armature in series with the battery. S_B is a series field on the booster. f_B is the controller-regulated field. S_B gives an excitation in the same direction as that of current flow. The controller gives a proper excitation to field f_B, so that the resultant magnetization of the two fields produces the required booster voltage.

The path of the current is from generator positive brush through C to junction point A. If the external load is less than the normal generator current, charge is sent into the battery, and part of the generator current goes through the booster field S_B, assisting f_B to produce a charging voltage. Another part of the generator current

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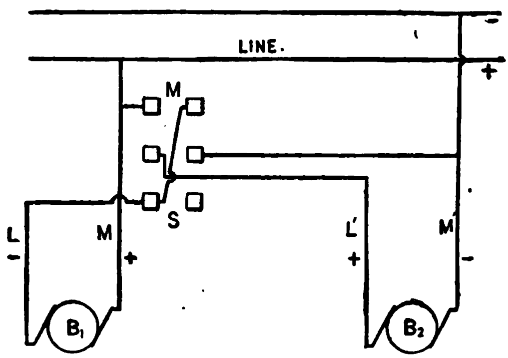


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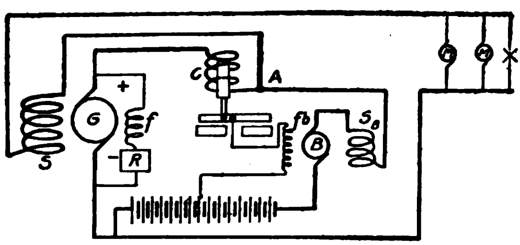


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goes from A through S and out to the line, supplying the external load MM. Since the generator field winding, S, is in series with the external load, the generator voltage will rise and fall with load changes. The series winding, S_B, carries a current that is proportional to the change in external load, hence the voltage due to this series coil will also rise and fall with change in the load. The winding f_B produces the booster voltage required to compensate for change in the pressure at the battery terminals, due to rate of charge discharge or to state of charge. The regulator must be controlled by a magnet, or other electrically energized device, which is responsive to both voltage and current, and not to current only as is usual with ordinary forms of booster controllers. Obviously if the generator current be kept constant, the generator energy output will fluctuate with variations in external load due to the voltage changes. For constant generator load, the current must *decrease* with *increase* in external load. This is produced by a voltage coil on the regulator. This coil is not shown in the figure. It is simply a winding around the magnet core, which is connected across the line. The pull it produces varies with the line voltage.

As an example consider a case in which

Normal generator output = 250 K.W.

Maximum output to line = 750 K.W.

Generator voltage no load = 500 volts = E.

Generator voltage maximum load = 600 volts = $E + I_x h$.

Percentage increase in generator output on maximum load = 5 per cent = ϕ.

Increase in generator voltage per ampere through the series field of generator and series field of booster = .08 volt = h.

To find the current and voltage at normal load:

$$\text{Watts} = W = I_0 (E + I_x h).$$

But since at normal load $I_0 = I_x$, the equation becomes

$$W = I_0 (E + I_0 h). \tag{195}$$

Solving,

$$I_0 = \sqrt{\left(\frac{E}{2h}\right)^2 + \frac{W}{h}} - \frac{E}{2h}. \tag{196}$$

Hence

$$I_0 = \sqrt{\left(\frac{500}{2 \times .08}\right)^2 + \frac{250{,}000}{.08}} - \frac{500}{2 \times .08} = 465 \text{ amperes.}$$

Generator voltage at normal load, then, is $500 + 465 \times .08 = 537.4$ volts.

For this condition the booster voltage is zero, and number of cells $= N = \frac{537.4}{2.1} = 256.$

For increase of load to 750 K.W., the generator output will be 250 (1 + .05) = 262.5 K.W.

Total external current is, (from equation 196),

$$I_x = \sqrt{\left(\frac{500}{2 \times .08}\right)^2 + \frac{750,000}{.08}} - \frac{500}{2 \times .08} = 1250 \text{ amperes.}$$

Voltage of system = 500 + 1250 × .08 = 600 volts.

Generator current is that necessary to give 262.5 K.W. at 600 volts $= \frac{262,500}{600} = 437.5$ amperes.

The booster voltage proceeds from two sources, one being the winding controlled by the regulator which produces a voltage in the direction of discharge, equal to the drop in battery voltage, and the other is that produced by the booster series field. The regulator field f_B is designed just as if the booster were to work on a constant potential circuit, as set forth in preceding chapters. The value of h for the series field is obviously the same as for the generator series field, being in this case .08 volt per ampere. The increase in booster voltage above that required to compensate for the drop in battery voltage, and due to S_B, is 600 − 537.4 = 62.6 volts, and this is produced by a field current of 1250 − 437.5 = 812.5 amperes.

If the volts per ampere-turn on the field = .02, the ampere-turns necessary to produce 62.6 volts $= \frac{62.6}{.02} = 3130$, and the number of series turns, T, on the booster field $= \frac{3130}{812.5} = 3.85$, or, say, 4 turns. The number of series turns on the generator field would be the same as the number on the booster field if each machine gives the same voltage per field ampere-turn. The voltage due to the series winding is added to the generator well above the knee of the magnetization curve, however, and it is probable that the generator volts per ampere-turn would be only .0125. The ampere-turns required to give an increase of 600 − 500 = 100 volts would be $\frac{100}{.0125} = 8000$, and since this is produced by 1250 amperes, the number of turns on the generator field $= \frac{8000}{1250} = 6.4$ turns.

On charge, if the external current be zero, and the generator field excitation be such as to give 500 volts at no load, the generator voltage will fall below 500 volts because there will be no series field, and the machine will act as a shunt dynamo, its voltage falling with increase in current to the battery. The voltage and current for this condition are found as follows.

Allowing 5 per cent reduction in the energy output of the generator for zero external load, the generator watts are 250,000 − 5% = 237,500 watts.

The equation for the load and voltage is

$$\text{Watts} = W = I\,(E - I h_1), \tag{197}$$

h_1 being the drop in voltage per ampere delivered by the dynamo, when no current flows through its series winding.

Solving,
$$I = \frac{E}{2\,h_1} \pm \sqrt{\left(\frac{E}{2\,h_1}\right)^2 - \frac{W}{h_1}}. \tag{198}$$

The positive sign before the radical cannot be used, as it gives values beyond the possibilities of the conditions. The negative sign therefore is the proper one to take.

For this case, if the generator voltage drop is approximately .08 volt per ampere,

$$I = \frac{500}{0.16} - \sqrt{\left(\frac{500}{0.16}\right)^2 - \frac{237{,}500}{.08}} = 516 \text{ amperes.}$$

The actual value of h_1 must be taken from the characteristic of the dynamo.

Generator and line voltage = 500 − 516 × .08 = 459 volts.

Assuming the maximum condition of 2.4 volts per cell, the battery voltage = 256 × 2.4 = 614 volts.

Booster volts = 614 − 459 = 155 volts.

Voltage due to booster series coil = 516 × .08 = 41 volts.

Therefore the regulator field winding must add 155 − 41 = 94 volts.

All the quantities are subject to correction for current used by booster driving motor, as set forth in Chapter XXXV. Also all the preceding computations are based on the assumption of straight characteristics which do not exist in practice. Therefore the factors, h and h_1 must be taken for extreme conditions at the points on the characteristics of dynamo and booster corresponding to the conditions assumed. Thus in the previous case, if 600 volts are

required on full load and the generator characteristic shows that 9600 ampere-turns in addition to the shunt turns are required, the series turns on the generator will be $\frac{9600}{1250} = 7.2$ turns. In practice this should be made 8 or 9 turns and the series winding then shunted to give the required voltage at the given output.

If the energy fluctuations produced by the voltage changes are to be taken by the generator, the controller will have only the single series winding as show in Fig. 218. In this case, the generator current will be $I_x - I(1 + \phi)$ on discharge, and $I_x - I_0 (I - \phi)$ on charge.

CHAPTER XXXVIII.

ADJUSTERS OF GENERATOR OUTPUT.

THE booster systems which have been described are designed to maintain a practically constant generator output regardless of the fluctuations and changes in the external load demand. The generator load is fixed at the average value of the external load, and in this way the amount of energy put in to the battery on charge is equal to that taken out on discharge. In power stations, however, the average load at different periods of the day varies greatly, and unless the booster controller is adjusted from hour to hour, the battery must receive as charge and give out on discharge at any time the difference between the average of the 24-hour load and the external load. This means that the battery would have to do much more work than if the adjustment were made during the day to give a generator output equal to the average of the external load for each short period of time. There would be intervals during which the battery would not only be taking up the load fluctuations but also receiving a continuous net charge, and other intervals when it would give a continuous net discharge. A battery working under such conditions would therefore have to be larger than if it only compensated for load fluctuations.

Consider Figs. 219 and 220. In each of the figures A is the graphic representation of external load, B is the load delivered by the generator, and C is the current to or from the battery. The ordinates of all three curves are for the same times or instants. Considering battery charge as negative, the sum of the battery and generator currents at any instant, is equal to the external load.

The curves in Fig. 219 are for a fixed average generator output, while those in Fig. 220 are for a variable average generator output, the generator load being changed at intervals to correspond with the value of the average external load over a short period of time. A study of these curves shows that where the average load is maintained constant, the ampere hours and the duration of charge and

discharge greatly exceed the corresponding quantities when the generator load is set for values at or near the average of the external demand. The magnitude of the fluctuations above and below the average, and which are equalized by the battery, do not differ appreciably in the two sets of curves, and the rate of battery dis-

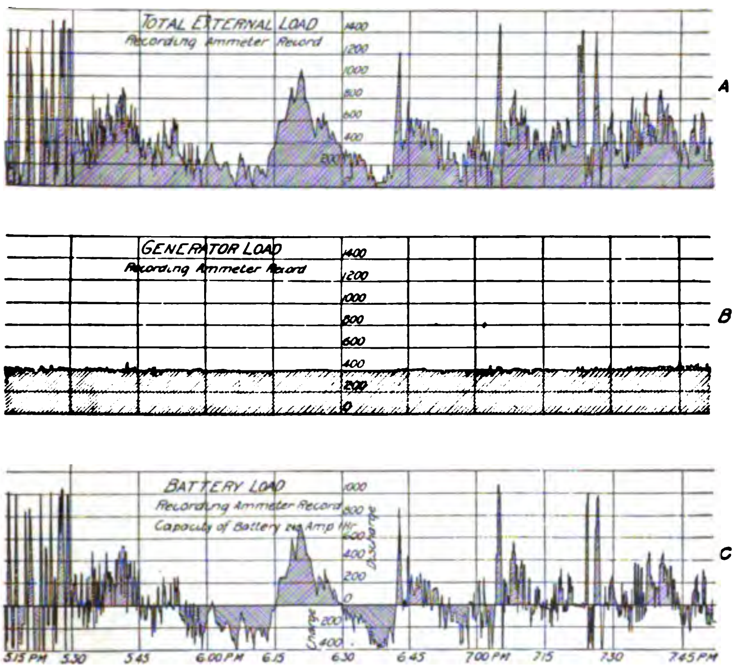


FIG. 219. Load Curves without Average Adjuster.

charge rises as high as 1100 amperes in both cases. The areas above and below the zero line in curves C, and which are proportional to the ampere hours put into or taken from the battery, are much greater in the case of the fixed generator average.

It has been usual to have the station attendants manually change the adjustment of the controllers at different periods during the day, the means of adjustment being as set forth in the preceding descriptions of the various systems.

R. C. Hull and J. L. Woodbridge have devised automatic adjusters* arranged to work in connection with any regulator which is

* Amer. Pats. Nos. 895760, 895825 and 964830.

provided with an adjusting shaft or screw or which may have its normal current regulated by a shunt. The present form in use consists of a small motor having its armature geared to the adjusting screw of the regulator, and connected across the booster armature so that the adjuster motor armature has impressed on it at any time a voltage equal to and in the same direction as

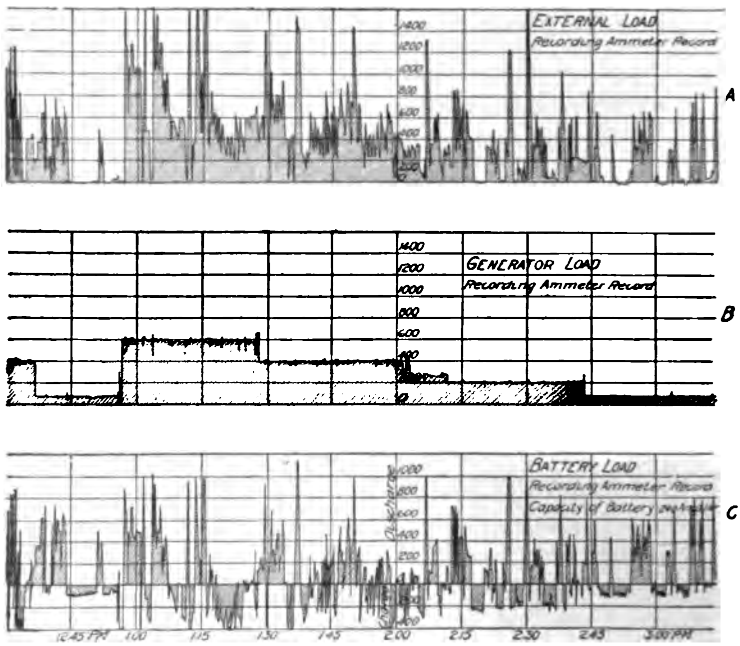


Fig. 220. Load Curves with Average Adjuster.

that of the booster. The motor field is shunt-wound and is connected across the line, the excitation being constant. The adjuster motor armature, therefore, rotates at a velocity and in a direction fixed by the booster voltage. The gearing between the adjuster motor armature and the adjusting screw is such that the rotation of the armature tends to reduce the current to or from the battery. Thus, if a heavy external load is suddenly imposed on the system, the booster regulator will produce a booster voltage such that the battery will supply the excess above the average generator current for which the regulator is set. This booster voltage causes the adjuster motor to start, and its rotation, com-

municated to the adjusting screw, acts on the regulator to increase slowly the generator output. If the heavy external load is momentary only, the movement of the adjusting screw will be very small and the generator current will not be substantially increased. If however the external load continues to exceed the generator output for several minutes, the average adjuster will continue to move until the generator output is increased to a new value, which

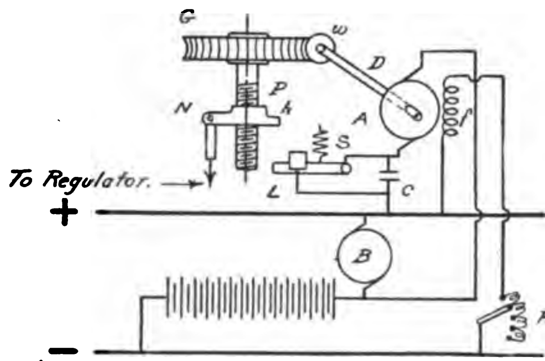


FIG. 221. Average Adjuster, Diagram of Connections.

is the average with respect to the new conditions. The battery therefore will take the rapid fluctuations, but the sustained changes will be gradually transferred to the generator.

The connections of this device are shown diagrammatically in Fig. 221. B is the booster armature, A the adjuster motor armature, f the motor field, D the motor armature shaft, w a worm meshing with the worm wheel, G, on screw shaft P. The field is connected across the line, rheostat R being in series with it. N is a nut working on P which moves along the screw shaft, its motion changing the adjustment of the regulator spring or shunt. L is a limit switch in series with the circuit from the booster brushes to the motor brushes. Switch L normally short circuits the aluminum cell E, so that current may pass to the armature A in either direction. When the switch is open, current can pass to the armature in one direction only, due to the well-known property of an aluminum cell of allowing current to flow through it in one direction but not in the opposite direction. Therefore, when L is opened by the projection h on the nut striking against it, the limit of travel in that direction is reached. Current, however, may pass

to the armature in the opposite direction and cause the nut N to move upwards. The switch L then is automatically closed by spring S. This switch is for the purpose of preventing any further

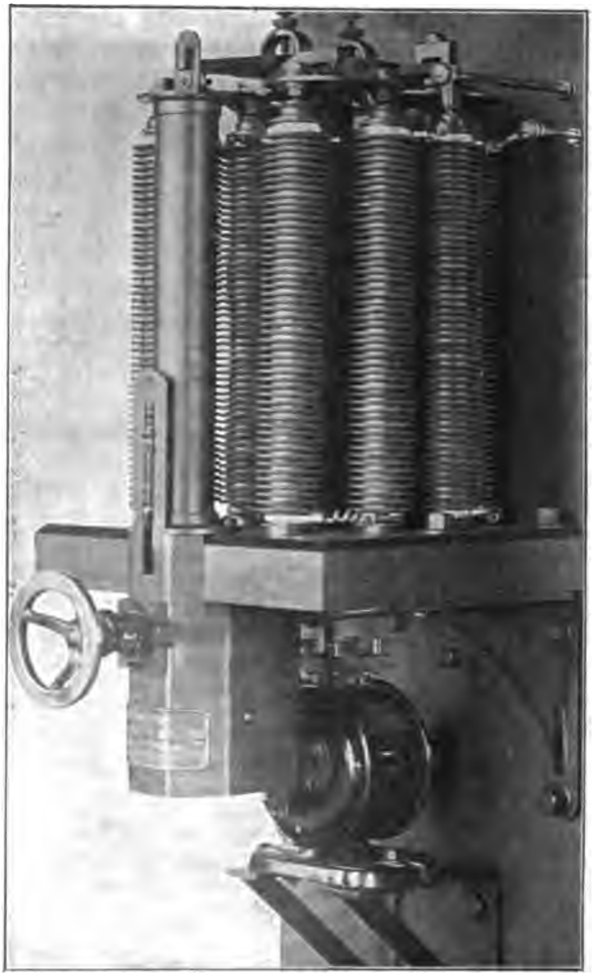


FIG. 222. Entz Controller with Average Adjuster, Front View.

augmentation of the generator load when it has been increased up to its maximum safe continuous output. Above this limit, the battery will take not only the rapid fluctuations but any sustained peaks also. Figs. 222 and 223 show this device working in con-

nection with a carbon pile regulator, Fig. 222 showing the regulating motor on a bracket just below the regulator, and Fig. 223 showing the end of the motor shaft carrying a worm which meshes with a worm wheel on a short shaft, set at an angle to the vertical. On this second shaft is a small pinion (not visible) which meshes



Fig. 223. Ents Controller with Average Adjuster, Rear View.

with teeth on the periphery of the large gear wheel which appears as a disc in the picture. This gear wheel is mounted on the screw shaft of the carbon regulator and is the same shaft as that on which the hand wheel seen in Fig. 222 is fastened. Movement of this shaft will change the spring tension and therefore the current through the regulator, as has been previously described in Chapter XXXIII.

CHAPTER XXXIX.

RHEOSTATS.

RHEOSTATS and variable resistances are used for booster field regulation and for controlling charge and discharge of small battery equipments, as has been described in preceding chapters. The variable resistances for controlling battery currents and voltages, are made in the form of ordinary rheostats having a moving arm and contact points over which it travels, as shown in Fig. 225.

In the case of resistances to carry heavy currents, these are usually made with the resistance units located in some convenient

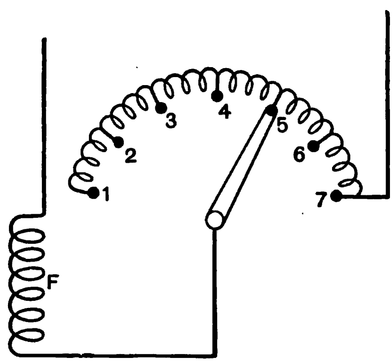


FIG. 225. Connections for Series Rheostat.

place, with connecting leads from the resistances to the proper contact points.

As a practical example of the calculation of rheostats for battery control, assume a storage battery which discharges on a lighting load until the pressure per cell falls to 1.8 volts, the normal pressure of the line to be maintained by rheostatic regulation for all conditions of battery charge above 1.8 volts per cell.

Line pressure = 110 volts.

$$\text{No. of cells} = \frac{110}{1.8} = 61.$$

Voltage fully charged = 2.1 × 61 = 128.1.

Maximum drop through rheostat = 128 − 110 = 18 volts.

Allow a change in voltage of 2 volts per step.

Maximum current = 100 amperes.

Minimum current = 10 amperes.

The resistances of the first sections must each give 2 volts drop with 100 amperes flowing. Resistance per section therefore = $\frac{2}{100}$ = 0.02 ohm. Resistance total for 100 amperes, 18 volts drop = 0.18 ohm. Number of sections to carry 100 amperes and give 0.02 volt change of drop in movement from one section to the next one = $\frac{0.18}{0.02}$ = 9 steps. If the current just below the maximum is 90 amperes, the total resistance necessary to give 18 volts drop = $\frac{18}{90}$ = 0.20. The resistance of the sections for 100 amperes is 0.18. Therefore the additional resistance which must be added to obtain 0.20 ohm = 0.20 − 0.18 = 0.02 ohm.

The volts drop per contact = 2 volts.

Resistance per contact = $\frac{2}{90}$ = 0.022 ohm.

Number of contacts = $\frac{0.022}{0.02}$ = 1.1, or one contact of 0.022 ohm.

Similarly for 80 amperes discharge the total resistance = $\frac{18}{80}$ = 0.222 ohm.

Resistance to be added to previous computation = 0.222 − 0.20 = 0.022.

Resistance per contact = $\frac{2}{80}$ = 0.025 ohm.

No. of contacts = $\frac{0.025}{0.022}$ = 1 contact of 0.025 ohm.

In a like manner the other sections are computed. The total resistance R is $\frac{18}{10}$ = 1.8 ohms. For the last steps, the resistance per step is $\frac{2}{10}$ = 0.2 ohm. The resistance of the immediately preceding series, carrying 20 amperes, is $\frac{18}{20}$ = 0.9. Therefore resistance of last series of sections = 1.8 − 0.9 = 0.9.

Number of steps in last series = $\frac{0.9}{0.2}$ = 4.5, which gives either 5 steps of 0.18 ohm each or 4 steps of 0.225 ohm each.

From the foregoing it may be seen that the practical computation of resistance sections for a rheostat is an approximation only.

The heat loss = EI. This is a maximum when I = 100 and E = 18, and is 1800 watts.

The rheostats used for booster regulation are sometimes con-

nected differently from the usual dynamo and motor regulating rheostat. The reason lies in the necessity of often impressing voltages across booster fields of from maximum to zero, and sometimes to a maximum in an opposite direction.

Fig. 225 shows the ordinary method of connecting rheostats. F is the coil or field across which the voltage must be varied. The other connections are obvious.

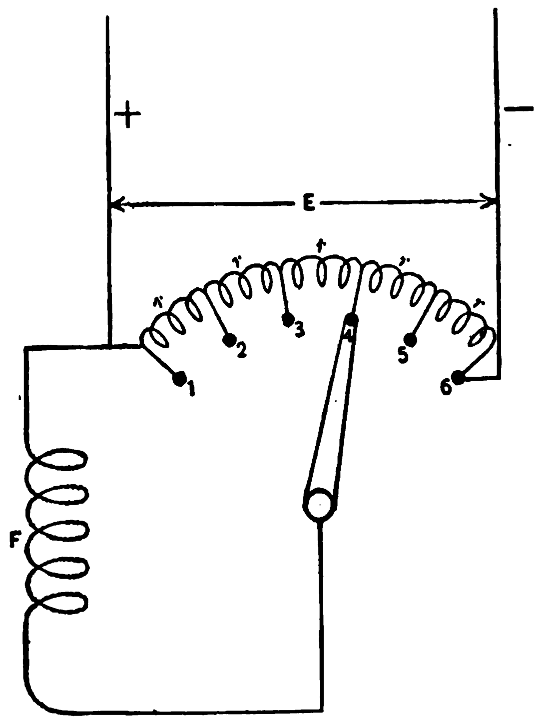


FIG. 226. Connections for Potentiometer Rheostat.

If the contact arm be moved in to the last contact 1, there is still a current flow through F, equal to $\frac{E}{R + R_1}$, in which R = resistance of the rheostat, R_1 that of the field coil F, and E the volts between the mains. Therefore, it is clearly impossible to reduce the voltage to zero with this form of rheostat, and even to approach it without breaking the circuit requires the resistance be very great.

Fig. 226 shows a method much used for connecting booster rheostats. In this case the resistance coils are connected across the line, and the voltage impressed on F for any movement of the arm is equal to the drop through that portion of the rheostat included in the circuit, and when the arm is on point 1 the voltage across F is zero.

A form of rheostat devised by the author* and shown in Fig. 227, has the advantage of permitting zero voltage to be attained and,

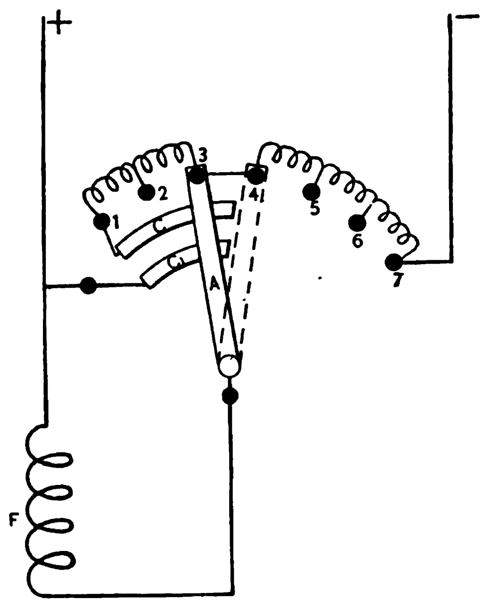


FIG. 227. Connections for Combination Rheostat.

at the same time, preventing the continuous energy loss which takes place across the rheostat coils when the form just described is used, whether the booster be in service or not.

The resistance connections do not differ from those of the ordinary rheostat except that one of the resistance coils is left out and two adjacent contacts are joined together. C and C_1 are short copper segments which are connected together by a contact plate on the under side of A.

When A is in the position shown by the full lines, the action and connections are exactly as in Fig. 226 and when A is on contact 1

* Amer. Pat. No. 754660.

the potential across F is zero. When A moves off 3 on to 4, the connection across the line, through the resistance coils, is opened, and the rheostat connections become as shown in Fig. 225. In passing from 3 to 4, less current flows through the coils from 4 to 7,

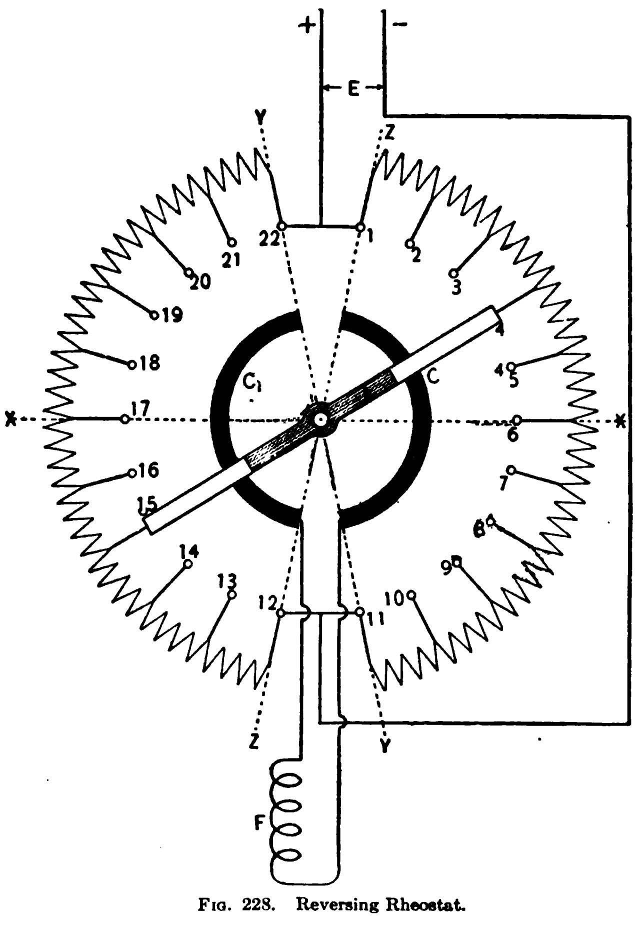


FIG. 228. Reversing Rheostat.

because the circuit through coils 1 to 3 is opened and a higher voltage is impressed on F, so that no coil is necessary between 3 and 4, as the volts across F increase from opening the circuit between 1 and C_1.

When it is desirable both to reverse the direction of current flow in the booster field as well as to vary its potential, the rheostat just

described, used with an ordinary reversing switch, will suffice, though reversing rheostats are often used. The scheme of connections of the reversing rheostat is shown in Fig. 228.

C_1 and C are copper segments across which F is connected, and they are joined to contact points by means of the arm A. The two ends of A are insulated from each other, and the current travels only from a contact to the nearest segment over the conducting portions of A.

Movement through approximately 90 degrees varies the potential across F from maximum to zero, the first being impressed when A coincides with the dotted line YY and the latter when it coincides with XX. After passing XX the current reverses in F, and when the arm reaches the position ZZ the opposite maximum is reached.

This form is somewhat elaborate and expensive and requires a large amount of switchboard space. Therefore, it is only installed with the larger sizes of boosters.

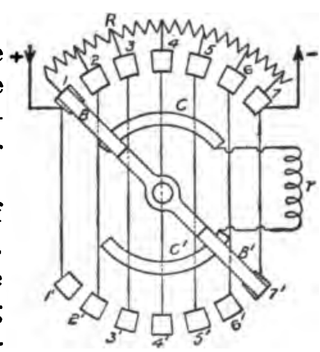


Fig. 229. Reversing Rheostat.

A cheaper, more compact form of reversing rheostat is shown in Fig. 229.

As seen from the diagram, the device is simply an ordinary rheostat having an auxiliary set of contact points corresponding with the series of points connected to the distributed resistance R_1. The auxiliary points are connected to corresponding main contacts as shown. A pair of copper segments C, C′ is provided, across which the field winding r is connected, and a rotating arm carrying the two conducting strips B and B′ is mounted on a central pivot. The conducting strips serve respectively to join the segment C to the upper contact points and C′ to the lower contact points. Obviously when the arm carrying B and B′ is at one extreme position the full voltage of the line is applied to r in one direction, and when in the other extreme position the full voltage is applied in a reverse direction. When in the middle position the voltage across r is zero.

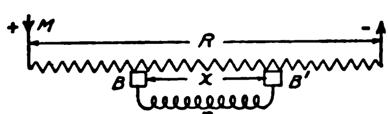


Fig. 230. Reversing Rheostat.

This arrangement is in effect the same as the diagrammatic scheme, Fig. 230. R is the resistance across the mains M, M′, r is the resistance of the winding to which the varying potential is to be applied, B and B′ are brushes working along R and approaching towards, or receding from, each other at the same rate of movement, x is that portion of R in parallel with r for any position of B and B′. The resistance of the circuit from M to B is $\frac{R - x}{2}$, and from B′ to M′ is also $\frac{R - x}{2}$. The resistance of that portion of the circuit from B to B′ is that of r and x in parallel and is $\frac{rx}{r + x}$. The total resistance, therefore, of the circuit from M to M′ is

$$R - x + \frac{rx}{r + x}. \tag{200}$$

Let E = voltage across the mains M, M′.
Then current flow through the circuit is

$$I = \frac{E}{R - x + \frac{rx}{r + x}}. \tag{201}$$

This current divides between r and x, and the amount flowing through each of these two parallel paths is inversely as their respective resistances.

Let i be the current through the field coil r, which is equal to $\frac{Ix}{r + x}$, and the current through resistance x is $\frac{Ir}{r + x}$, their sum being equal to I.

Substituting the value of I in equation 201, the current through r is

$$i = \frac{Ex}{(r + x)\left(R - x + \frac{rx}{r + x}\right)} = \frac{Ex}{R(r + x) - x^2} \tag{202}$$

and
$$x = \frac{R}{2} - \frac{E}{2i} \pm \sqrt{\left(\frac{R}{2} - \frac{E}{2i}\right)^2 + Rr}\,. \tag{203}$$

From which it is seen that x apparently has two values. The quantity under the radical is however greater than the terms before it, therefore the use of the minus sign before the radical would give a negative value of x, which is impossible. Hence the positive sign only may be used. In practice it is simpler to compute only

a few values of i or x and from these plot a curve from which any intermediate values may be taken. Usually it is easier to assign values to x and compute corresponding values of i from equation 202.

As an example assume

$$E = 100 \text{ volts.}$$
$$R = 250 \text{ ohms.}$$
$$r = 100 \text{ ohms.}$$

i to vary from zero to 1 ampere in either direction, changing 0.04 ampere per step.

The number of steps will be

$$\frac{1.00}{0.04} + 1 = 51 \text{ steps.}$$

From equation 203, for $i = 0.5$ ampere

$$x = \frac{250}{2} \frac{100}{2 \times 0.5} + \sqrt{\left(\frac{250}{2} \frac{100}{2 \times 0.5}\right)^2 + 250 \times 100}$$
$$= 25 + 160 = 185 \text{ ohms.}$$

Taking the easier method of computation and assigning values to x to solve for i, by equation 202, the following results are obtained:

For $x = 10$	$i = 0.0365$ ampere
$x = 50$	$i = 0.142$
$x = 100$	$i = 0.250$
$x = 150$	$i = 0.375$
$x = 200$	$i = 0.572$
$x = 225$	$i = 0.724$
$x = 250$	$i = 1.00$

From these values of x and i the curve Fig. 231 is plotted, and from this any value of either quantity may be taken by inspection. Thus for $i = 0.04$ ampere, the resistance between the middle contact and the next adjacent one on either side is $11\frac{1}{2}$ ohms. For $i = .08$ ampere the resistance between the middle point and the second contact is 25 ohms. The resistance therefore from the first contact to the second is $25 - 11.5 = 13.5$ ohms. For $i = 0.12$, $x = 40$; therefore the resistance between second and third contacts $= 40 - 25 = 15$ ohms. These values are taken direct from the curve as shown by the dotted lines forming the series of steps along the curve. The vertical distance from one step to

the next one represents, to scale, the resistance between the two steps.

To compute the heat loss in the rheostat.

$$\text{Watts loss, L} = I^2(R - x) + (I - i)^2 x. \qquad (204)$$

For any value of x the corresponding watts loss may be calculated from this equation.

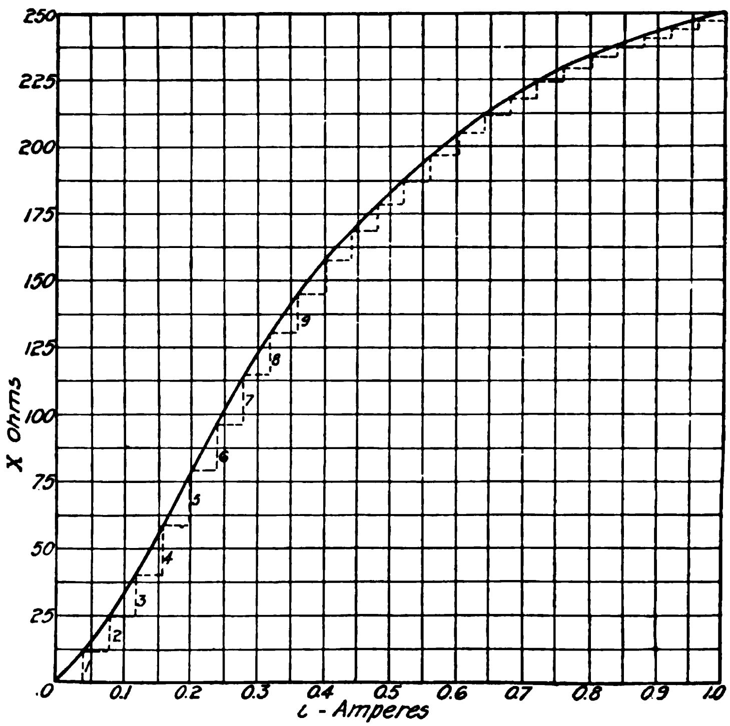


FIG. 231. Curve of Division of Resistances for Reversing Rheostat.

The maximum loss takes place when

$$x = \frac{R}{2} - 2r + \sqrt{\left(\frac{R}{2} - 2r\right)^2 + 3Rr}. \qquad (205)$$

For the foregoing case, $x = 209$ ohms when loss is maximum and the loss = 53.3 watts. The value of x for maximum loss is found by substituting the values of I and i in equation 204, differentiating, equating to zero and solving for x. Thus, taking the

value of I in equation 201 and i in equation 202 and substituting, equation 204 becomes

$$L = \left(\frac{E\,(r + x)}{Rr + Rx - x^2}\right)^2 (R - x) + \left(\frac{E\,(r + x) - Ex}{Rr + Rx - x^2}\right)^2 x. \quad (206)$$

Neglecting E, which is a constant multiplier, and combining, the equation becomes

$$L = \frac{(r + x)^2\,(R - x) + r^2 x}{(Rr + (R - x)\,x)^2}. \quad (207)$$

Placing this quantity equal to u and differentiating,

$$\frac{du}{dx} = x^2 - (R - 4\,r)\;x - 3\,Rr. \quad (208)$$

Equating to zero and solving for x,

$$x = \tfrac{1}{2}\,R - 2\,r \pm \sqrt{(\tfrac{1}{2}R - 2\,r) + 3R\,r}. \quad (209)$$

When the use of the negative sign before the radical will give a negative result, the plus sign is the only one to use, which gives the equation 205.

CHAPTER XL.

CIRCUIT BREAKERS AND INSTRUMENTS.

CIRCUIT breakers are used for the protection of the battery and the machinery with which it is connected.

The overload circuit breaker is so familiar to engineers as to require no description here.

These are used in battery circuits to prevent excessive discharge of the battery, and in booster circuits to protect these machines.

If a booster having a series winding, is left connected to the system, and the driving motor circuit be interrupted, it will act as a series motor, finally speeding up to the point of destruction. Therefore, when boosters of this character are installed, and the motors provided with overload breakers, there must be a breaker in the booster circuit which interlocks — either mechanically or electrically — with the motor breaker, so that the opening of the motor circuit causes a simultaneous opening of the booster circuit.

In the mechanical device there is a lever connected to the motor breaker which controls the latch on the booster breaker, and it is so arranged that in case the motor breaker opens, the lever will operate the catch on the booster breaker, causing it to release and break the circuit.

When operated electrically, the booster breaker, in addition to the usual series coils, is provided with an auxiliary coil, which is generally placed inside the series coil and around the plunger, its terminals being connected to the bus bars through a contact device. This contact is on the motor circuit breaker, and so arranged that if the motor breaker opens, the moving arm bridges the two contact pieces when it falls back in its open position, thus closing the circuit through the auxiliary coil on the booster breaker, and energizing it. This coil is so designed that the bus voltage will cause the plunger to rise and release the latch, tripping the breaker and opening the booster circuit.

The overload and no-voltage breaker is used in the motor circuit. This breaker will open the circuit in the event of excessive current to the motor or in case the circuit is interrupted, or if for any

reason the voltage is removed from the circuit. Frequently this breaker is combined with the motor-starting rheostat.

The underload circuit breaker is used to prevent the battery from discharging if the charging dynamo should be shut down or the polarity of the charging source be reversed. This circuit breaker is made in several forms, but the principle of them all is practically the same.

The breaker is held closed by the passage of charging current through a magnet winding which acts directly or by holding down a latch. When the current reaches a predetermined minimum, a spring, which continuously tends to open the breaker, overpowers the magnetizing force of the diminishing current, and the breaker opens. Since no reversal can take place without the current passing through zero, this breaker effectually prevents reversal. Usually, the underload breaker is intended to be cut out of circuit on discharge, and if it is a polarized instrument, must be cut out, as it will not permit a discharge to pass through it. If not a polarized breaker, discharge may be taken through it, but at the beginning of reversal, and until the current has reversed and passed the minimum value it must be held closed by hand.

The carrying capacity of the underload breaker, necessarily is that which corresponds to the maximum amperes of charge.

The underload and overload breaker is a device that combines both the functions of the two separate breakers. It is much used in booster circuits instead of the underload breaker, as it serves to protect the circuit against either excess or reversal of current.

The instruments used in storage battery installations are voltmeters, amperemeters, voltmeter switches, wattmeters and ground detectors.

Voltmeters and *amperemeters* should always be permanent magnet controlled instruments, because in storage battery work the direction of current flow and polarities are important. No instrument that will give an indication in the same direction with current passing through it in either direction should be used. To this latter class belong the Siemens dynamometer, the electromagnetic and hot-wire instruments; in fact any instrument that will work on alternating-current circuits.

Amperemeters in battery circuits should have their zero points in the middle of the scale, the needle being free to move in either direction, so that both charge and discharge currents are measured,

the direction of swing showing the direction of the current. Instruments of this kind cost no more than standard amperemeters with the needle moving in one direction only, provided the total length of scale is the same in each case. For equivalent capacity and cost, therefore, the scale divisions are twice as close together in the double-reading as in the single-reading instrument. Amperemeters of this kind are necessarily shunt instruments.



FIG. 233. Voltmeter Plug Switch.

Voltmeter switches are of two kinds. One that is most used in battery installations consists of a series of pairs of points working in connection with a pair of contact segments, which latter are joined to the voltmeter terminals. A pair of contact arms movable about a central pivot impresses the potential of any pair of points across the pair of segments, and through them, on the voltmeter. In this way a single voltmeter may serve to show the voltage across any number of points.

Another form is the plug switch shown in Fig. 233. This comprises four terminals having cavities into which mating plugs, fastened to an insulating support plate, may be thrust. The four mating plugs are divided into two pairs, the plugs of each pair being connected together but the pairs insulated from each other. Therefore, when the plugs are pushed into position, corresponding terminals are connected through the plugs. If two terminals are connected to the points across which the voltage is to be taken, and the other two connected to the voltmeter, the proper voltage will be indicated when the plugs are pushed into place.

By using several sets of terminals, or receptacles, each having one pair of terminals connected to the voltmeter, different voltages may be read by shifting the plug from one set to another.

This switch, while reliable and satisfactory, is too expensive if more than three voltages must be indicated, and the rotating, multiple-point switch becomes the more suitable.

Wattmeters and ground detectors are the same in every respect as the standard forms used or any electrical circuit and require no description here.

CHAPTER XLI.

COMPUTATION OF BATTERY CAPACITY.

In order to compute the size of battery necessary to perform certain work, it is necessary to plot a load curve showing the current consumption at any time during the twenty-four hours. From this, the maximum, minimum and average current flow, the work required of the battery and the proper capacity for it, may all be determined with the help of the factors K, as given in Chapter VIII.

In order to facilitate these calculations, the two curves shown in

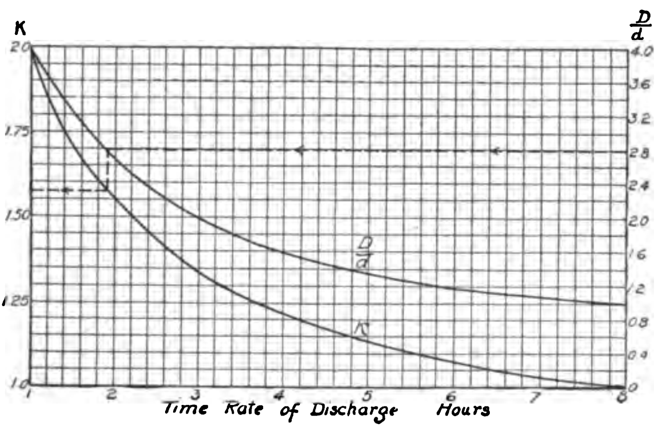


Fig. 234. Curve of Values of "K."

Fig. 234 have been prepared. The vertical scale on the right refers to the upper curve, and the left vertical scale refers to the lower curve. D is any discharge in amperes, while d is the amperes discharge at the 8-hour rate. $\frac{D}{d}$ is found and the value taken on the right-hand vertical scale. Follow this horizontal thus located until it intersects the upper curve marked $\frac{D}{d}$. At the point of intersection, a vertical down to the horizontal scale will show the time rate of discharge at the amperes of flow = D. The vertical

also intersects the lower curve, marked K. At this point of intersection, a horizontal to the left scale will give the value of K for the discharge rate D.

Example: What is the value of K for a discharge of 84 amperes from a battery having an 8-hour rate of 30 amperes? $\frac{D}{d} = \frac{84}{30} = 2.8$. Following the horizontal from 2.8 to curve $\frac{D}{d}$, then vertically down to curve K, then horizontally to the left to scale K, the value 1.56 is located. It may also be seen that 84 amperes discharge is the 1 hour and 57 minute rate of this battery. If $\frac{D}{d}$ should exceed 4, then the discharge is in excess of this 1-hour rate, and is too high except for a few moments.

These curves are only approximations, as they may vary considerably with different types and makes of batteries, but they fairly represent average practice.

The data could be expressed in a single curve if the rate of discharge were omitted, and $\frac{D}{d}$ placed on the horizontal scale in place of the time.

The *regulating rate* of a battery is the maximum rate of discharge or charge allowable for batteries working on rapidly fluctuating loads and which charge or discharge continuously only for a few seconds and never longer than two minutes. In America the regulating rate is 8 times the 8-hour rate. The amperes charge or discharge allowable at the regulating rate are therefore equal to the ampere-hours capacity of the battery at the 8-hour rate. Thus a 1000-ampere-hour battery is one which will discharge 125 amperes continuously for 8 hours at 70 degrees temperature. The regulating rate of this battery is $8 \times 125 = 1000$ amperes.

In computing the size of battery necessary to supply a given fluctuating load, it is essential that the current for driving the booster motor be included in the maximum load, as has been previously pointed out.

To determine the size of battery required to supply current continuously over a given load peak, a trial and error method of calculation must be adopted.

Take, as an example, the load diagram as shown in Fig. 235. The dotted line shows the generator output, while the heavy line

shows the station output. The difference between the two at any instant, is given out, or absorbed by, the battery. The diagonal shading shows charge and the cross hatching, discharge.

The peaks being some hours apart, may be considered as independent and having no bearing on each other, since the battery has

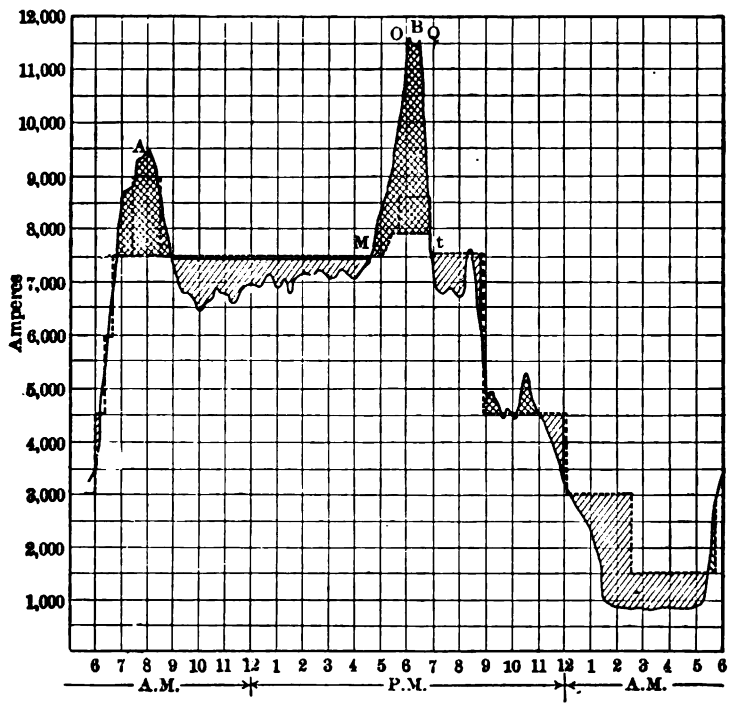


FIG. 235. Load Curve.

sufficient time to regain full charge after it has discharged on peak A, before discharge on peak B begins. Therefore, the capacity of the battery will be that required to cover the greater peak, which, by inspection, is seen to be peak B, and it only becomes necessary to determine the ampere hours which the battery must discharge to cover this peak. This is shown enlarged in Fig. 236, to better illustrate the method of computation. The diagram is divided into a number of vertical laminæ by vertical lines. The area of each of these laminæ represents, to proper scale, the ampere hours supplied to the outside circuit during the time covered by its base.

The short horizontal lines *s.p.r.d.z* represent the average discharge rates of the different divisions. The capacity required is first assumed to be 10 per cent greater than the total ampere hours of the peak at the rate of discharge equal to the length of the peak base. The total ampere hours are 4400 and time of discharge $2\frac{1}{4}$ hours. K for $2\frac{1}{4}$-hour rate is about 1.50. $4400 \times 1.50 = 6600$ = approximate ampere hours required to carry the peak. Adopting this as the trial value, the use of the vertical divisions is resorted to for determining the final value.

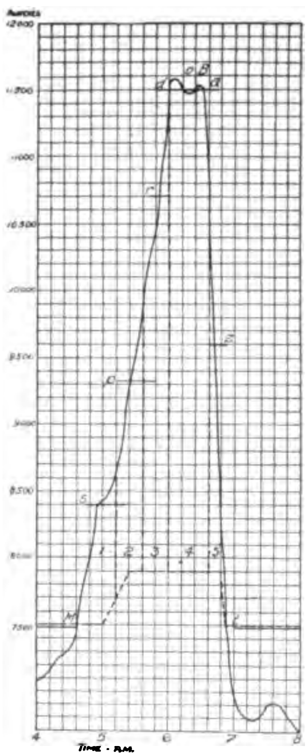


FIG. 236. Section of Load Curve.

Division No. 1 is 380 ampere hours at an average discharge rate of 900 amperes, which is about the 7-hour rate for a 6600-ampere-hour battery. Therefore, the battery capacity in ampere hours required for division No. 1, referred to the 8-hour rate, is $380 \times 1.03 = 391.4$. Similarly, division No. 2 is 560 ampere hours at 1400 amperes, which is the $3\frac{3}{4}$-hour rate with K = 1.25, and the ampere hours referred to 8-hour rate = $560 \times 1.25 = 700$. No. 3 = 1060, rate 2700 = $1\frac{3}{4}$-hour rate; K = 1.68; ampere hours = $1060 \times 1.68 = 1780$.

No. 4 = 2160 ampere hours, rate 3600, which is greater than the one-hour rate. This would not be so objectionable if the time were only ten or fifteen minutes, but the base of this division is 36 minutes, which is too long to continue a discharge at such a high rate. Therefore, a new trial capacity must be adopted. Division No. 5 requires but little capacity. The sum of divisions 1, 2 and 3, as found, is 2871 referred to the 8-hour rate. If the one-hour rate be taken as the highest allowable, then K = 2 for division 4, and the ampere hours = $2160 \times 2 = 4320$. Adding to this the 2871 previously found, the result is 7181, or, say, 7200 ampere hours. The rates are now less for this than for the 6600-ampere-hour battery,

and therefore the capacity should be great enough to take care of No. 5 also.

Beginning again as before: Division No. 1 is 380 ampere hours, and as 900 amperes is the 8-hour rate, K = 1 and the battery capacity for this division is 380 ampere hours.

No. 2 = 560 ampere hours at the rate of 1400 amperes, which is the 4½-hour rate. K = 1.2, and ampere hours = 560 × 1.2 = 672.

No. 3 = 1060 ampere hours; rate 2700 amperes = 1¾-hour rate. K = 1.63, ampere hours = 1.63 × 1060 = 1730.

No. 4 = 2160 ampere hours; rate 3600 amperes = 1-hour rate. K = 2; ampere hours = 2160 × 2 = 4320.

No. 5 = 240 ampere hours; rate = 1700 amperes = 3½-hour rate. K = 1.31 ampere hours = 240 × 1.31 = 314. Total ampere hours = 7416. Therefore the assumed capacity of 7200 is also too small, and a 7400-ampere-hour battery would be required. If this size be adopted, the total referred to the 8-hour rate will be less than 7416, as the discharge rates will be less and the factors K correspondingly reduced.

To the capacity thus found, at least ten per cent should be added to cover the loss of capacity which takes place after the battery has been some time in service, and toward the end of its life. For the case under consideration, this would make the proper capacity to install 7400 + 740 = 8140 ampere hours at the 8-hour rate.

As will be seen, this is a trial and error method, the accuracy of the result depending on the number of divisions into which a load curve may be divided.

In computing battery capacity, it seldom is necessary to take into account the portion of the curve over which charge takes place, as in most load curves there are short peaks and long hollows, and during the time over which the hollows extend the battery fills up at a moderate rate.

There are some instances, however, where the charging rate is necessarily high, and in such cases the minimum allowable size of the battery is that in which the 1-hour rate of charge is never exceeded. Rapid charge is much more injurious to a cell than rapid discharge, and in no case should current be passed into a cell at a rate higher than the 1-hour rate, but even this is not good practice, and should not be allowed if it is to last longer than twenty minutes continuously.

As an example, consider the load curve shown in Fig. 237, which shows the station output, for one hour, from a rotary converter sub-station feeding an electric railway, the line pressure being 550 volts. The readings are taken at 30-second intervals.

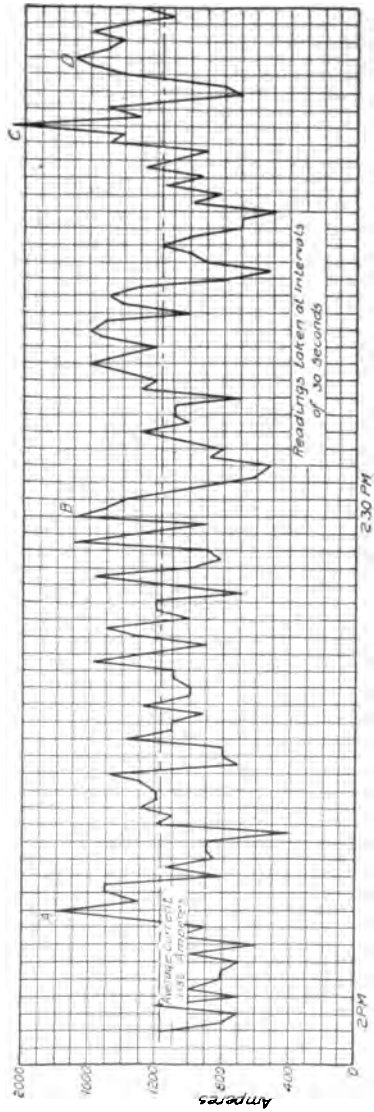


FIG. 237. Curve of Fluctuating Load.

In this case, the rotary converters are to supply the average current only, plus 5 per cent on overloads and minus 5 per cent on underloads. This average is 1180 amperes, and on overload is 1180 + 59 = 1239 amperes, and on underload = 1180 − 59 = 1121 amperes.

The maximum load on the station is 2100 amperes, or 861 amperes more than the maximum output of the rotary. The minimum load is 400 amperes, or 721 amperes less than the minimum output to be maintained on the rotary converter.

If a reversible booster is in series with the converter, the current from the battery required by the booster motor on maximum discharge with minimum battery voltage is, from equation 182, $= \frac{118 \times 861}{0.76 \times 550 - 118} = 305.3$ amperes. The total maximum discharge is therefore 861 + 305.3 = 1166.3 amperes, and the size of the battery will have a capacity of 1166.3 or 1200 ampere hours on this basis. The figure 0.76 is the combined efficiency of booster and motor. On charge,

the current to the battery is that in excess of the external load minus the motor current. If the maximum regulating battery voltage be 2.4 volts per cell, and the number of cells = 262, the maximum battery pressure = 262 × 2.4 = 629 volts.

Booster voltage on charge = 629 − 550 = 79 volts.

From equation 183, the motor current is

$$\frac{79 \times 721}{0.76 \times 550 + 79} = 114.5 \text{ amperes.}$$

The current to the battery therefore is 721 − 114.5 = 606.5 amperes.

This allowance for motor current which is *added* to the discharge and *subtracted* from the charge, means that the average generator output is not 1180 amperes but some greater amount which shall have a value such that the total energy delivered to the battery shall be equal to the total energy abstracted from it, over a given period of time. In order to find this correct average, the readings above and below the line of load average must each be corrected for the booster current required at that particular value of line current. A new curve is plotted from these corrected readings, and the average is found which has a value such that if a horizontal line be drawn through the curve, the sum of all the areas between the line and those portions of the new curve above it, is equal to the sum of all the areas lying below the line and included between it and the curve.

This correction will be generally very small, as the extreme conditions of battery charge and discharge will obtain but seldom if the equipment is properly operated. No accuracy in this computation is required, as the assumed load on which it is based may never exist, or if it does, may never repeat itself. A general approximation based on the average of several load curves and general experience is all that is necessary, keeping in mind the maximum possible conditions that may obtain, and fixing the size of the battery to carry any reasonable load that it may be subjected to.

Referring to Fig. 237, the maximum discharge peak is at C. The current does not reach so high a value as at peaks A and D, but it lasts much longer and the ampere hours of discharge are greater.

When discharging over peak D, the average rate of discharge is about 375 amperes, which is the 2¾-hour rate of a 1200-ampere-hour cell, while the actual time of discharge is only 3½ minutes. So, if

the maximum size, as determined by the requirements of charge and discharge rates, be adopted, the battery will have a capacity many times greater than necessary to supply current to the peak loads.

The battery, as here computed, will be unnecessarily large because the maxima of charge and discharge are sharp-pointed and are only instantaneous — lasting but a few seconds at most. If a horizontal be drawn across from the 1800-ampere mark on the left-hand vertical, it will cut the peaks A and C only, and the greatest duration of discharge above this line is at peak D and lasts only 45 seconds. A battery, therefore, the regulating discharge rate of which rises up to the 1800-ampere mark, may be considered as sufficiently large for all practical purposes. The regulating discharge rate, then, is $1800 - 1180 = 620$ amperes. To this must be added the maximum motor current, which has been found to be 305 amperes, making a total of 925 amperes that the battery must discharge without falling below 1.65 volts per cell. This corresponds to a 925-ampere-hour battery at the 8-hour rate.

From the foregoing, it is seen that the selection of size of battery is largely a matter of judgment and requires experience and a thorough knowledge of the subject. These examples are given to indicate the methods by which the approximate size is determined.

Obviously, the size of battery is greatly influenced by the character of the plant, prospects for increase, and probable character of load increase. Also, the question of fuel and labor costs, combined with the above considerations, may make a great difference in the size of the equipment that will be productive of greatest economy.

CHAPTER XLII.

DIRECT-CURRENT SYSTEMS.

THERE are many ways of arranging batteries to perform the various functions before outlined, and it is only possible to describe a few of the most important.

The simplest case of regulation is that in which a battery is connected across the line at some distance from the power station and "floats," charging and discharging with variation in the line drop. This case is specially treated in Chapter XLIII.

Power Storage Systems.

The simplest case of power storage is that of the small, isolated plant, such as is found in apartment houses or on yachts, where the load after 11 or 12 o'clock P. M. is light enough to be entirely carried by the battery, the generators being shut down.

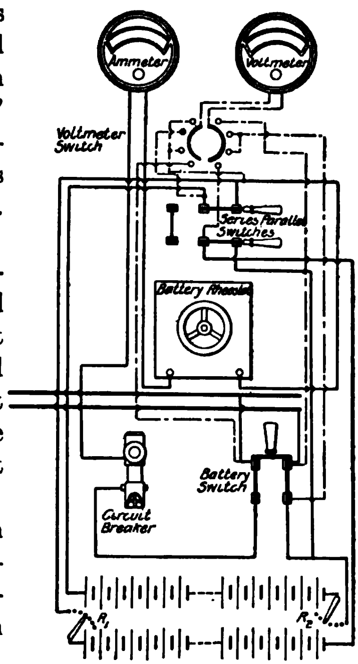


FIG. 238. Connections for Parallel Charge, Series Discharge.

In Fig. 238 is shown one system of connections by which this is accomplished. The battery is separated into two halves for charging in parallel

A series-parallel switch is provided and connected as shown.

When the blades of this switch are thrown to the right, connecting the central and right-hand contacts, the charging current passes into the two halves of the battery, which are in parallel and therefore much below the voltage of the generator. The path of the current is through the main battery rheostat, the circuit breaker, to the resistances R_1 and R_2, through which it passes, the

current flow being regulated by the battery rheostat, and caused to divide equally between the halves of the battery by means of R_1 and R_2.

When the series-parallel switch is thrown to the left it is in a position for discharge. The path of the current can easily be traced, and it is seen that the two halves of the battery are now in series, their voltage being much higher than that of the line. This voltage is reduced by manipulating the resistances through which the current passes.

Sometimes an underload circuit breaker is included in which case it is connected so that it is cut out of circuit when the series-parallel is thrown to the position for discharge. R_1 and R_2 have comparatively small resistances and carrying capacities. They are designed to take the maximum charging current to one-half the battery, which is half the total current supplied from the mains. Since they serve only to equalize the current flow between the two halves of the battery, the resistance required is but small. If the total drop through R_1 or R_2 is as much as 12 per cent of the voltage of the circuit when the normal charge is being put into the batteries, the resistance will be ample. R_1 and R_2 are cut out of circuit on discharge, the battery rheostat serving to regulate the voltage. The main rheostat therefore, must have a carrying capacity through part of its resistance equal to the maximum discharge current, the resistance over this portion being so distributed that the voltage change produced by movement of the arm from one contact to the next will not exceed 3 volts. The number of contacts carrying this maximum discharge current will be such that the total resistance of this section will produce a drop equal to 25 per cent of the normal circuit voltage when the maximum discharge current is flowing, this being approximately the change in cell voltage from beginning to end of discharge.

The resistance sections at the end of the rheostat opposite to the sections carrying the maximum discharge, which carry the minimum current, and the drop due to these resistance sections, plus the resistance of all the other sections in the battery rheostat, must be 25 per cent of the normal line voltage. In other words, it must be so constructed that any current between the maximum and minimum can be made to give a drop ranging from 3 volts to 25 per cent of the line voltage, in steps not exceeding 3 volts.

The number of cells in equipments of this kind are always taken as equal to $\frac{E}{1.8}$, in which E = line voltage and 1.8 = minimum cell voltage. If the cells were discharged to a lower voltage, they would have a short life, as the discharge is not momentary but sustained; also, the greater number of cells would increase the cost and give a higher voltage at the beginning of discharge, which would require greater resistance losses to maintain the line voltage constant.

This system has the advantage of being simple and cheap. Its disadvantages are loss of energy in the resistance, both on charge and discharge, and the fact that the constancy of voltage or discharge depends on constancy of load, since the current is regulated by the ohmic drop of the resistance.

A modification of this system is shown in Fig. 239. Here the cells are divided into three groups, which are charged as follows:

Groups 1 and 2 in series.
Groups 2 and 3 in series.
Groups 1 and 3 in series.

Each combination is charged one-half the time required to fully charge a cell at the rate that current is supplied.

They are all discharged in series.

This latter modification has the advantage of requiring less resistance in series with the charging current, as on charge there are two-thirds of the total cells in series, as compared to one-half in the preceding case.

Referring to the figure, the switch consists of eleven contacts, 1 to 11 inclusive, and three movable contact pieces, A, B and C, each having a contact brush or piece at either end. Group I is connected to contact points 1, 2, 6 and 7. Group II to 3, 4, 8 and 9, and group III to 5, 10 and 11, the terminals being also connected to 1 and 11. R is the adjustable resistance.

In the position shown, groups I and II are charging. Calling *a* the lower end of the moving segment A, the dotted lines show the angular position of *a* around the circle and the connections that are made for each angular position are easily traceable. In position 1, as shown, groups I and II are in series on charge, in position 2, groups II and III and in position 3 groups I and III are being charged in series, while in position 4 all the groups are in series on discharge.

The time of charging in this system is $1\frac{1}{2}$ times as long as required in the single series for the same current rates.

These systems of grouping cells for charging are applicable only to small plants. Where heavy currents are to be carried, the

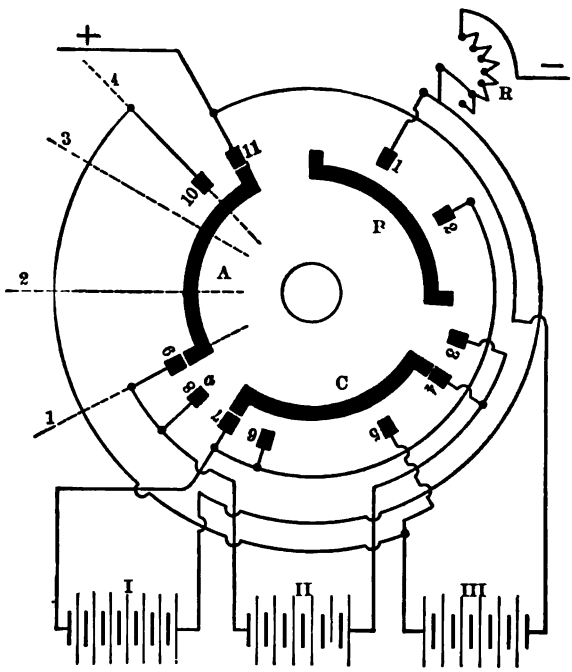


FIG. 239. Diagram for Parallel Connections of Storage Cells.

switching devices become so cumbersome that boosters are cheaper and more easily handled; besides the losses in the resistances with large currents would be impracticable.

A system which is sometimes used for country house and private plants is shown in Fig. 240. The generator is driven by a gasoline or kerosene engine, the battery being charged during the day and the current at night is furnished from the battery only.

A is an amperemeter, U an underload circuit breaker, V a voltmeter and V.M.S. a three-point voltmeter switch connected to show the voltage of (1) the generator; (2) the line and (3) the battery.

In this, the maximum generator voltage is equal to $N \times 2.6$, and the voltage of the line $= N \times 1.8$. When S_1 is closed down-

wards, and S_2 open, the battery is connected for charging, and the current is regulated by varying the generator voltage. This is done with rheostat R.

When S_1 is open, and S_2 is closed, the battery discharges to the line, its voltage being regulated by the end cell switch S_3.

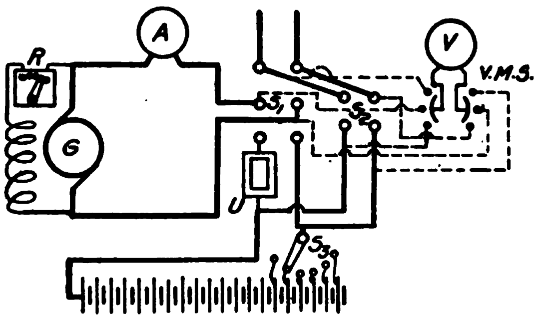


FIG. 240. Connections for Charging Battery from Dynamo.

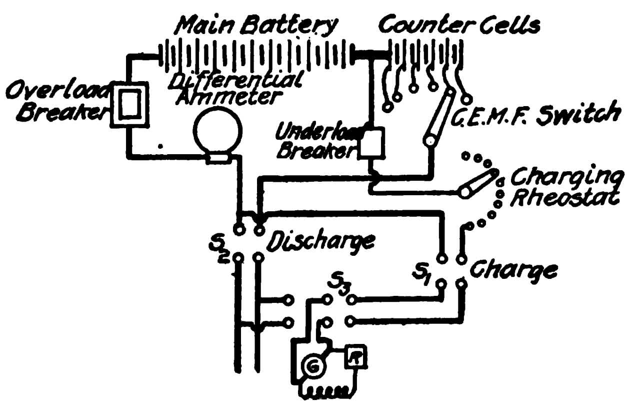


FIG. 241. Connections of Plant using Counter Cells for Regulation.

When S_2 is closed, and S_1 thrown to the upper position, the generator voltage being reduced to equal that of the line, the generator and battery may be made to work in parallel.

No current can be furnished the line when the battery is being charged except at a higher voltage than normal.

Another system, which has the advantage of permitting the battery and generator to work in parallel during charge or discharge, is shown in Fig. 241.

As is seen, there are counter electro-motive force cells connected in series with the battery. The charging current goes in over S_1, passing through the resistance which regulates it and the underload breaker. The voltage of the generator is higher than that of the service bus bars, the excess reaching .6 N volts at end of charge, where N = number of cells in series.

The current to the line does not pass through the underload breaker and rheostat, but passes through the counter electromotive force cells and S_2, the opposing voltage reducing the generator pressure to the proper amount. This is regulated by the number of counter cells in the circuit which are switched in as the generator voltage rises. The number of counter cells required = $\frac{0.6\text{ N}}{2} = 0.3\text{ N}$, where N = number of main cells in series.

The double-pole, double-throw switch, S_3, when thrown to the right, connects the generator to the battery system and through the counter cells to the line. When thrown to the left, the generator is connected directly to the line, its voltage of course being reduced by the field rheostat R to that of the line, and the battery may then be discharged in parallel with G to carry a peak. When S_3 is open the battery carries the entire load.

This system, in common with all counter cell systems, is practically obsolete, except for the conditions specified below, as better results can be obtained by using certain of the battery cells as end cells. The use of counter cells does not reduce the number of cells required in the battery, and the expense of the equipment is increased by the addition of counter cells, and they are also an additional complication.

There is one class of plant only where counter cells are suitable, and that is the isolated plant which is charged during the day by an attendant who either does not stay in the station or who has not sufficient intelligence to cut out the battery end cells as they become charged. With the counter cells the plant may be left on charge without attention if the supply circuit be left open. If current is used on the external circuit while charging proceeds, the attendant must be on hand to switch in counter cells, otherwise the external voltage will rise far above the normal.

The best of the systems which operate without boosters is that shown in Fig. 242. There are two end cell switches, the similar points of each being connected to the same end cell, as shown.

The current from the generator goes through the switch S_1 to the left-hand terminals of the double-pole, double-throw switch S_2. When S_2 is thrown to the left position, the battery is cut out of service. One of the generator leads is permanently connected to the left battery terminal, passing through the underload circuit

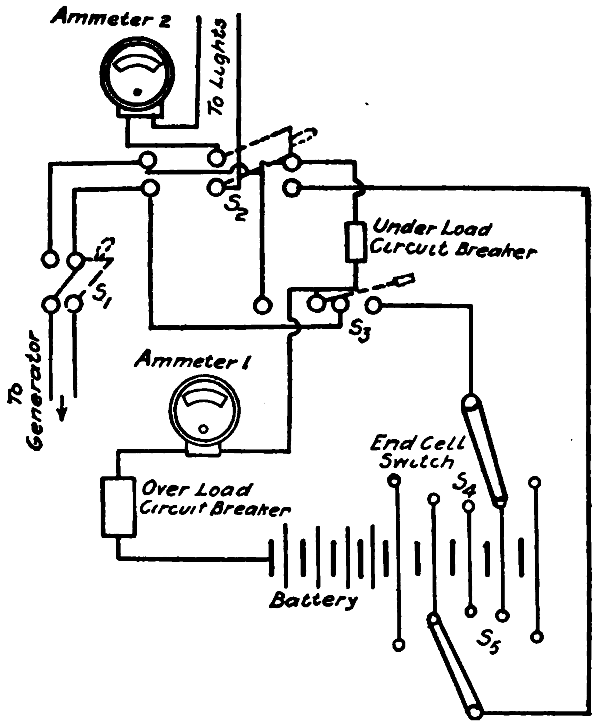


FIG. 242. Connections of No-Booster System with Two End Cell Switches.

breaker, two-way reading ampere meter and overload breaker. The other generator lead is connected to the end cell switch by the double-break, single-pole, double-throw switch S_3, when it is thrown to the right.

When the battery is charging, S_2 and S_3 are thrown to the right. The generator voltage must be in excess of that of the line by an amount sufficient to force current into the cells. All current to the line passes through the end cells included between the contacts of S_4 and S_5, on which the respective arms of these two switches rest, and the line voltage is less than the generator voltage by an

amount equal to the voltage of the number of cells in series between these two contacts. With S_2 on the right-hand and S_3 on the left-hand contacts, the underload circuit breaker is cut out and the battery ready to discharge, either in parallel with the generator, or alone if S_1 be opened.

This system has the advantage over the preceding one, of requiring no additional counter cells, though the end cells in this case must be sufficiently large to pass the sum of the external and charging currents through them. In nearly every case in practice, the end cells need not be increased above the size of those in the main battery.

Fig. 243 shows the switchboard for this system, the connections being indicated by dotted lines. The switches and amperemeters on it correspond with those shown in the diagrammatic view. In addition, there is a voltmeter and a switch, S_6, which opens the line circuit.

In all the foregoing systems the generators should be shunt wound, or if series machines, should have a cell put in the series winding as explained in Chapter XXXII.

Power Storage Systems with Boosters.

The simplest case of the application of boosters to storage battery plants is that of the shunt booster, in a station where the battery is used for storage only. Such a system is diagrammatically shown in Fig. 244.

The booster field is excited from the line as shown. With switch 1 thrown to the right the battery is charging. When thrown to the left the booster is cut out and the battery discharges, the voltage being regulated by the end cell switch 5.

If the booster is used reversibly, the end cells and end cell switch 5 are not required, though the size of the booster is increased, as explained in a previous chapter.

Usually this system is much cheaper to install and is higher in efficiency than the systems without boosters, unless the plant be a very small one.

This becomes evident when it is remembered that the generator must be capable of giving a higher voltage than the line when no booster is used, unless the cells be arranged for parallel charging and the charging current controlled by an energy-consuming resistance. The capacity of the generator is therefore increased. Sometimes this increase is just sufficient to require the next larger

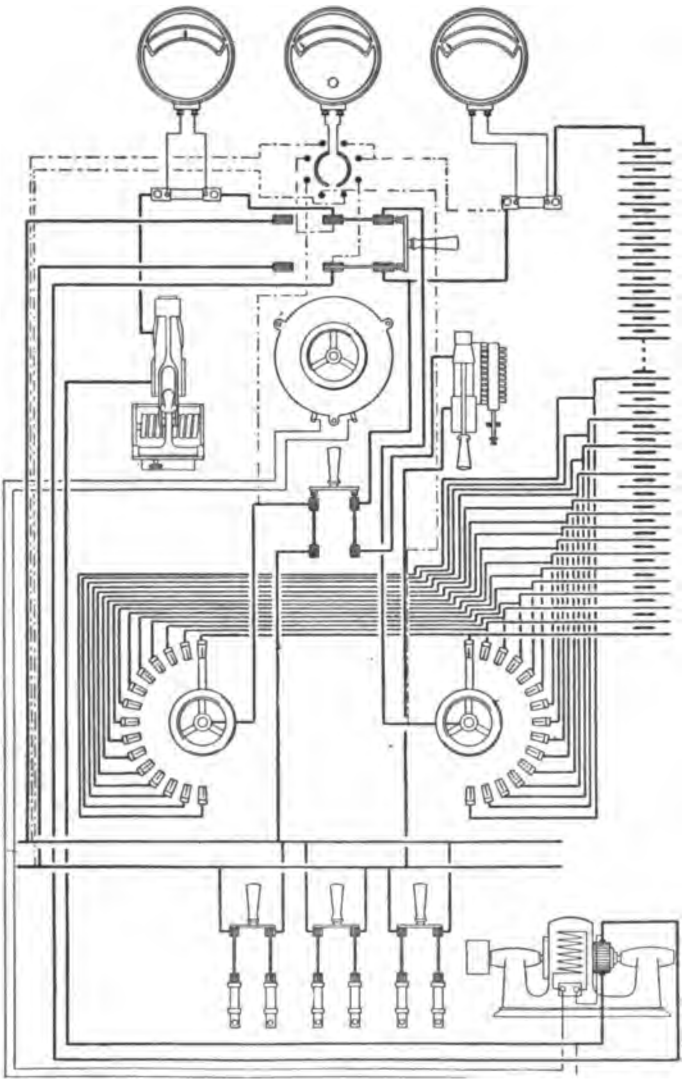


FIG. 243. Switchboard for No-Booster Plant with Two End Cell Switches.

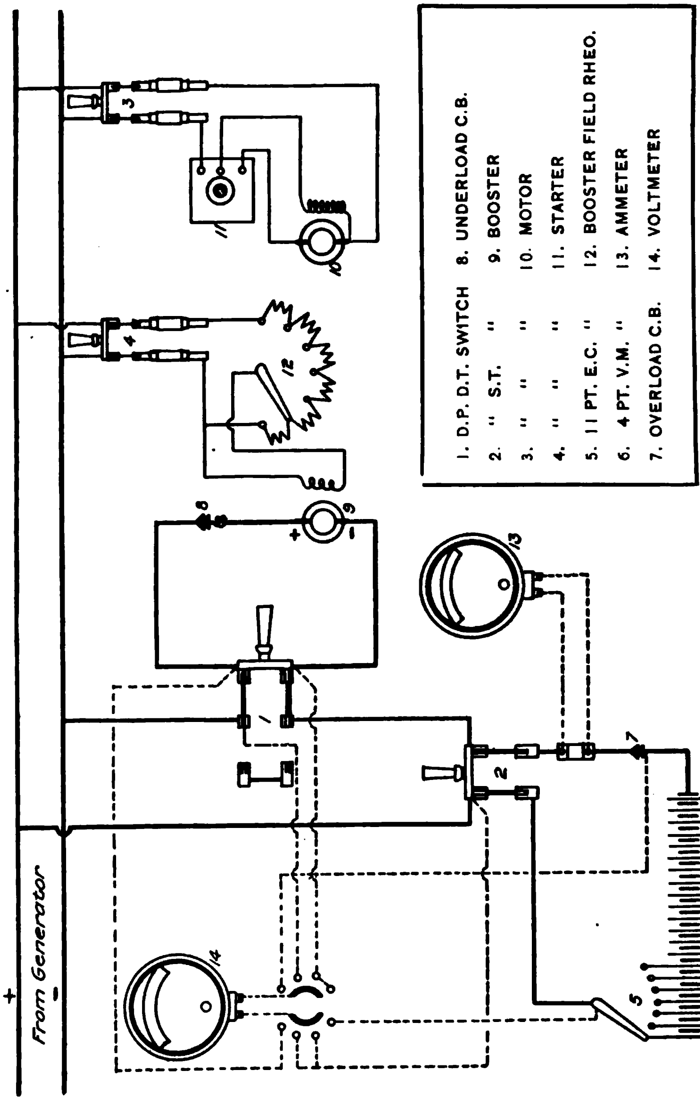
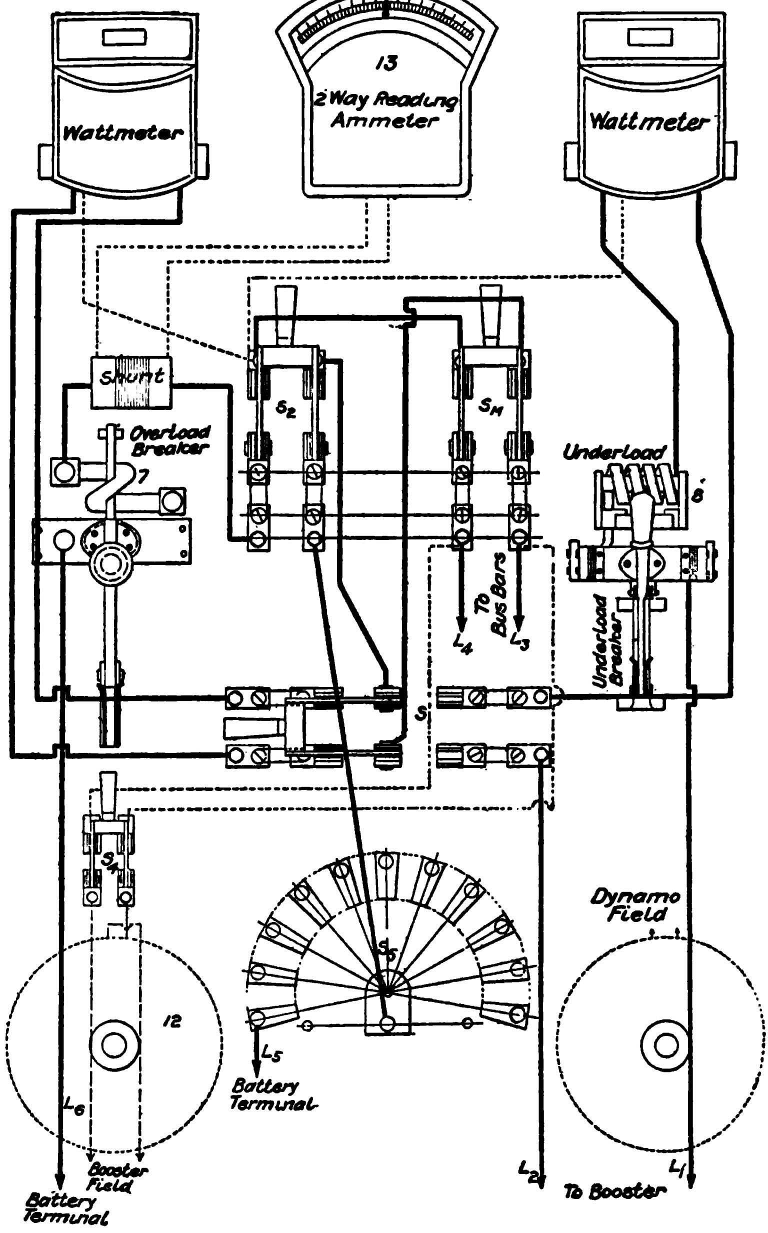


FIG. 244. Switchboard Connections for Plant with Charging Booster.


Wattmeter
13
2 Way Reading Ammeter
Wattmeter
Shunt
Overload Breaker
7
S_2
S_M
Underload
8
To Bus Bars
L_4
L_3
Underload Breaker
S
S_4
S_5
Dynamo Field
12
L_5
Battery Terminal
L_6
Booster Field
Battery Terminal
L_2
L_1
To Booster

size of standard frame, in which case the increased generator cost would be very much greater than that of booster and driving motor. In addition, switches and leads are often saved, all of which are expensive and contribute to make the cost of no-booster systems excessive, as compared with those in which boosters are used.

Plate IV shows a switchboard for this system. In addition to the instruments shown in the diagrammatic sketch, wattmeters are included; S_3 being connected to take in the wattmeters. On charge, switch 1 is thrown to the right, putting one wattmeter and the underload breaker in circuit. On discharge, these are cut out by throwing switch 1 to the left, which, at the same time, puts the other wattmeter in circuit.

The motor switch and starting box are not on this panel.

The voltmeter and voltmeter switch are not shown, but the connections should be such as to show (1) voltage across the bus bars; (2) voltage of bus bars plus booster; (3) voltage of battery as indicated in Fig. 244. Before beginning charge the switch 2 is opened, the main switch closed and switch 1 thrown to the right-hand contacts.

The booster voltage is then brought up to such a value that bus bar plus booster voltage = about 10 volts more than battery voltage. Then switch 2 is closed and the charging current adjusted by slowly raising the booster voltage.

Fig. 244a is a switchboard diagram for the same character of installation as that shown in Fig. 244 and Plate IV. It has no wattmeters and the motor connections are shown. The upper, middle circuit-breaker is the underload breaker and is cut out of circuit when the double-throw switch is thrown to the left. The breakers on either side of the underload breaker are to prevent excessive overloads, the one on the left being in the motor circuit while the one on the right is in the battery circuit. R is the booster field rheostat and M.S.B. is the motor starting box.

Storage and Regulating Batteries Using Automatic Boosters.

The use of the various automatic boosters has been explained in the discussion of each, so it is not necessary here to go into detail as to the various ways in which they may be installed. Complete diagrams of booster systems are given in Chapters XXXII, XXXIII and XXXIV. Diagrams 188, 202 and 212 are representative of present-day practice.

The principal factors in the design of various booster-controlled

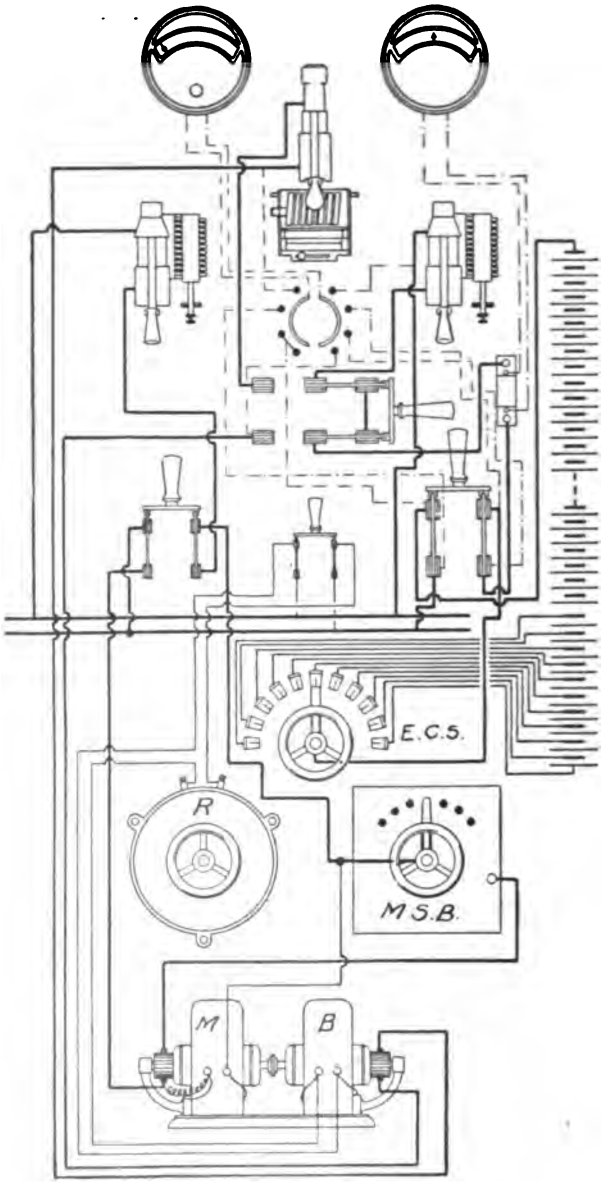


FIG. 244a.

equipments will here be briefly discussed. Consider the case of a plant in which a mixed motor and lighting service is to be supplied, the former load having rapid fluctuations. If the load is all concentrated within a short distance of the generators, as in an isolated plant, and the battery is to furnish current for lighting when the generators are shut down, the non-reversible booster system may be used. If the line voltage on the lighting bus bars is to be 110, the number of cells, inclusive of end cells, will be $\frac{110}{1.8} = 61$. Number of end cells $= \frac{61 \times 2.1 - 110}{2.1} = 61 - \frac{110}{2.1} = 9$ end cells.

Take minimum booster voltage = 0 volts.

The range of voltage through which the 61 cells will work on regulation is 1.8 to 2.3 volts or a total change of 30 volts. Half of this is 15 volts, which is the normal excess of the power bus bars above the lighting bus bar pressure. The power bus bar pressure will be $110 + 15 = 125$ volts.

Normal voltage of booster = 15 volts.

Maximum voltage of booster = 30 volts.

Minimum voltage of booster = 0.

And normal voltage of power line is 125 volts. Maximum is 140 and minimum is 110 volts.

With these data and a knowledge of the maximum average load to be supplied continuously to the power bus bars, the booster and controller may be computed.

The end cell switch will have 10 points or one point more than the number of end cells.

Assume that the variable load consists of three elevators, each taking 75 amperes starting and 35 amperes running current. Maximum current to elevators $= 75 + 75 + 35 = 185$ amperes; that is, the starting of two elevators simultaneously while one is running will probably often occur. The average current to elevators for the 24 hours is 40 amperes. This quantity may be approximated by assuming a given number of trips of each elevator per diem, with the time and current consumption, allowing from three to four seconds at the starting rate. A wattmeter in the circuit, or an ampere meter, is the best way to fix on the average if the plant is already installed. If not, some assumption must be made and a working figure arrived at.

Assume further that the load curve of the plant is as shown in

Fig. 245, and the period of shut-down is to be from 1 A.M. to 1 P.M. the following day, as indicated by the cross-hatched area, which represents battery discharge. This area shows a battery capacity of 840 ampere hours.

The battery capacity required for regulation only, neglecting motor current, is 185 − 40 = 145 amperes at the regulating rate, which is equal to 145 ampere hours referred to the 8-hour rate.

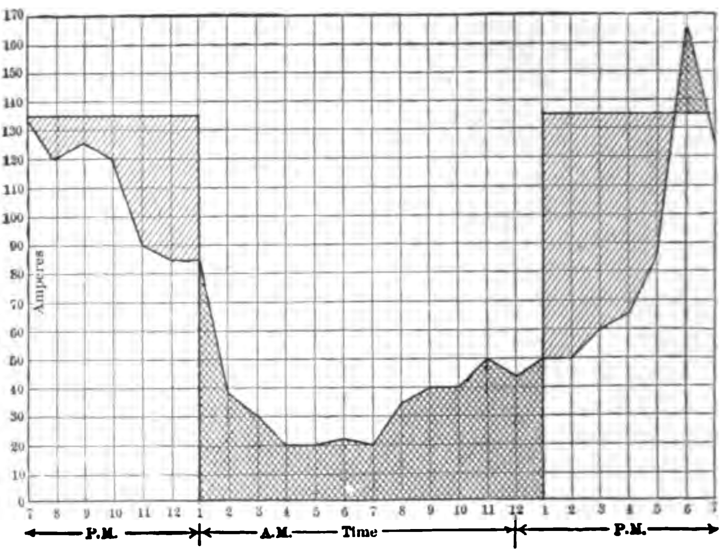


FIG. 245. Load Curve.

The maximum amperes passing through the booster into the battery are 40 for the elevator load and 170 for the charging, making 210. The armature of a constant-current booster would have to be large enough to take this current for at least two hours continuously.

If the booster were a reversible machine in series with the battery, its armature would have to carry 170 + 145 = 315 amperes as a maximum, but this load would last only a few moments. The booster would have to be large enough to carry the steady load of 170 amperes continuously, plus say 30 per cent of the maximum fluctuating load. Its capacity therefore would be 170 + 0.30 × 145 = 213.5 amperes normal rating. The non-reversible booster is practically the same size, but it is more convenient to install where

end cell switches are used, and therefore will be adopted for this case.

Maximum voltage on "boiling" = 2.6 × 61 = 158 volts, which is the maximum voltage required. 158 − 110 = 48 = maximum booster voltage for overcharging.

If the combined motor and booster efficiency = 76 per cent, the normal generator current when passing 40 amperes to the load will be, from equation 183,

$$I_G = 40 + \frac{40 \times 15}{0.76 \times 125} = 46.3 \text{ amperes.}$$

If the regulation is to be 5 per cent, then on maximum discharge the generator current = 46.3 × 1.05 = 48.6 amperes. Since the booster voltage is zero, the motor current will be practically zero, being only the free running current of the machines. If this is 1.6 amperes, the net battery discharge to the line will be 185 − (46.3 − 1.6) = 40.3 amperes. The battery must therefore be large enough to deliver this current without falling below 1.8 volts per cell. This corresponds approximately to the 1-hour rate, for which the factor K = 2. The capacity referred to the 8-hour rate is therefore 140.3 × 2 = 280.6 ampere hours. For the storage service before computed, it must be about three times as large as this and, therefore, will be of ample capacity for all regulating requirements of this plant.

If the booster is to carry both the charging current of 170 amperes and the 40 amperes average regulating current = 210 amperes, generator load will be, from equation 183,

$$I_G = 210 + \frac{210 \times 15}{0.76 \times 125} = 243 \text{ amperes;}$$

which is the current the booster must be able to carry at least two hours.

Size of booster = 243 × 48 = 10.48 K.W.

Maximum motor capacity is required when passing

$$243 - 46.3 \times .05 = 240.7$$

amperes to the power bus bars with the maximum regulating pressure of 30 volts.

Motor capacity = (243 − 46.3 × .05) 30 = 7.22 K.W.

Allowing 85 efficiency of booster, the actual power required is $\frac{7.22}{0.85}$ = 8.5 K.W., or practically 11 horse-power.

The general scheme of connections is shown in Fig. 246, the several devices being designated. As is seen, the lighting load is connected across one set of bus bars to which the generator feeds directly, while the variable power load is connected across a separate set of bus bars, the current passing to them through the booster. The automatic voltage regulator is clearly shown, and its action has been fully described in Chapter XXXIV. Fig. 247 shows the complete switchboard connections for a system of this kind, the generator and lighting load not being included on the panel.

Numbers 1 to 8 inclusive represent knife switches; 9 is an end cell switch; 10 is a 3-point voltmeter switch; 11 an overload circuit

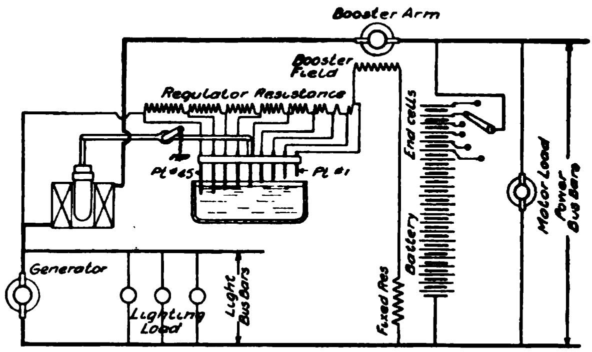


Fig. 246. Diagram of System Supplying both Lights and a Variable Motor Load.

breaker; 12 an over and underload circuit breaker; 13 an overload and no-voltage circuit breaker; 14 is a motor-starting resistance; 15, booster field rheostat; 16, automatic regulator; 17, booster motor; 18, booster; 19, voltmeter; and 20, a 2-way reading amperemeter.

As an example of an *electric railway plant* take the following conditions:

Maximum load (fluctuating),	2000 amperes
Minimum " "	400 "
Average " "	1100 "
Generator voltage,	550 volts
Degree of regulation required,	5 per cent.

Type of booster, reversible.

If the usual practice is followed of making the battery voltage on open circuit equal to the bus bar voltage, the number of cells

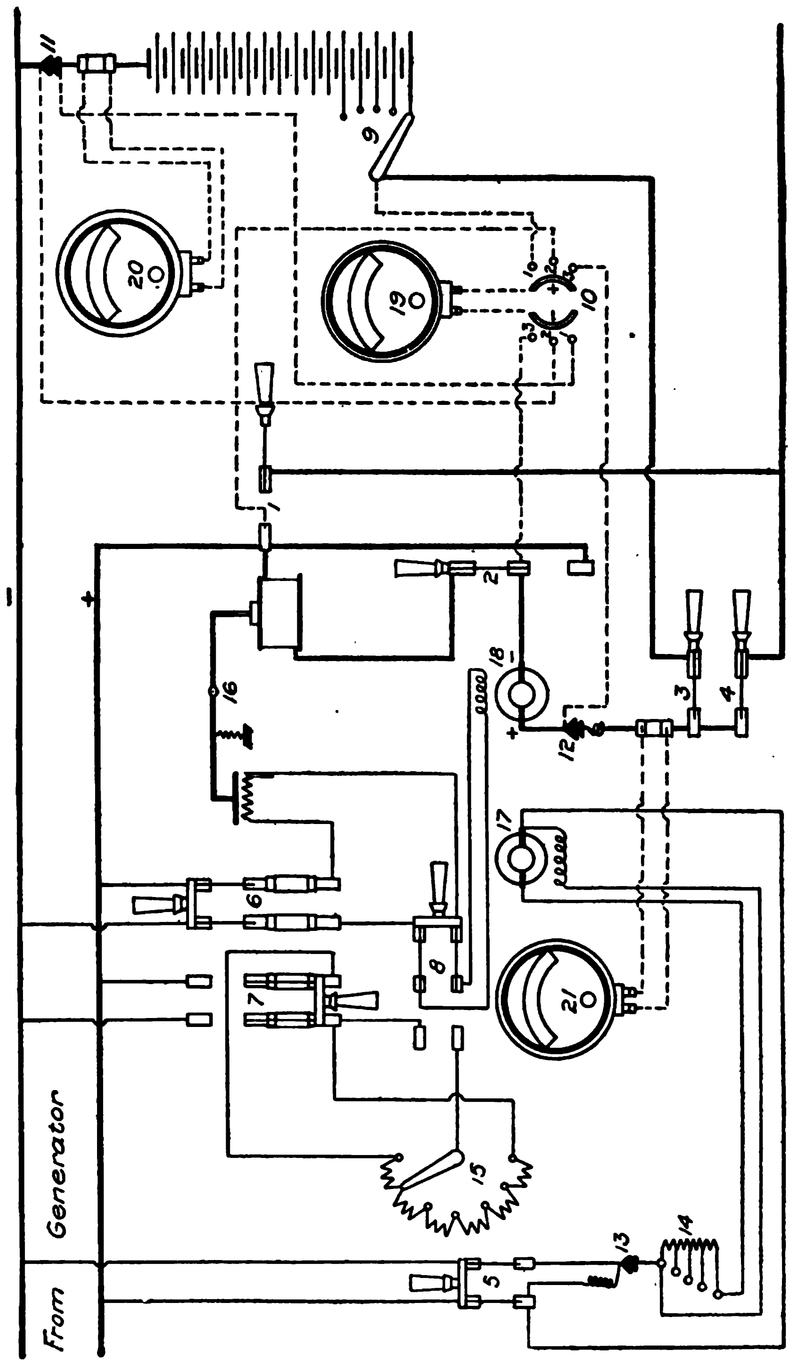


Fig. 247. Connections for Reversible Booster System.

will be $\frac{550}{2.05} = 268$ cells, 2.05 being the open circuit voltage of the particular type of cell here considered.

Maximum battery voltage on charge = 268 × 2.6 = 696.8 volts.

Maximum booster volts = 696.8 − 550 = 146.8 volts.

When maximum discharge takes place and the battery voltage falls to 1.65 volts per cell, the booster volts = 550 − (1.65 × 268) = 107.8, say 108 volts.

Current to line from battery = 2000 − 1100 = 900 amperes.

Maximum motor current (from equation 182) is

$$I_B = \frac{108 \times 900}{(0.76 \times 550) - 108} = 313.5 \text{ amperes,}$$

0.76 being assumed efficiency of booster and motor combined.

The maximum discharge rate of the battery when down to 1.65 volts per cell is 900 + 313.5 = 1213.5 amperes. Taking this as the regulating rate, the size of the battery is 1200 ampere hours at the 8-hour rate.

Booster capacity on basis of 1213 amperes maximum current = 1213 × 146.8 = 177 K.W. If a machine with a compensated winding be used, 25 per cent of this capacity will be great enough, = 0.25 × 177 = 44.5, say 45 K.W.

Maximum booster output = 1213 × 108 = 131.1 K.W. If motor is an inter-pole or compensated machine, 25 per cent of this output will be great enough for the motor capacity if corrected for booster efficiency. Assume efficiency of booster at 85 per cent.

$$\text{Then size of motor} = \frac{131.1 \times 0.25}{0.85} = 38.7, \text{ say } 40 \text{ K.W.}$$

The connections for this equipment, and all switches and instruments required, except voltmeters and voltmeter switch are shown in Fig. 202.

The controller is the Entz carbon pile.

In certain plants where the discharges of the battery to the line are heavy and frequent, the number of battery cells installed are in excess of the number which give a floating voltage equal to that of the bus bars. In this case the open circuit battery voltage is higher than that of the bus bars, and under normal conditions of load the booster voltage is not zero, but has a value equal to the difference between the battery voltage and that of the line and opposing the battery voltage. The booster energy at normal load

is, however, zero, because current neither goes into nor is discharged from the battery.

When the external load increases, the booster voltage diminishes and allows the battery to discharge, the booster current increasing as its voltage decreases, until at the point where the booster pressure reaches zero, the booster energy is again zero. Any higher discharge requires that the booster voltage rise in the opposite direction, *i.e.*, assisting the battery, the booster current and pressure now rising together, the booster energy increasing as their product. The objects of this arrangement are:

(1) To reduce the time lag of discharge, which is done by the reduction of an existing magnetic field instead of the production of one: the time of reducing the electro-motive force of a dynamo-electric machine being much less than that required to create an equal electro-motive force; (2) to reduce the motor current required for maximum discharge and thereby reduce the size of the battery cells; (3) to be able to fully discharge the battery, even if the booster be out of commission.

Consider conditions the same as given in the preceding example, except that the normal floating voltage of the battery is 50 volts higher than that of the line, namely 600 volts.

Number of cells at 2.05 volts per cell = 292.

Maximum charging voltage = $292 \times 2.6 = 759$ volts.

Booster voltage for charging = $759 - 550 = 209$ volts.

Maximum booster volts on discharge = $550 - 292 \times 1.65 = 68$ volts.

$$\text{Maximum motor current} = \frac{68 \times 900}{0.76 \times 550 - 68} = 174.8 \text{ amperes.}$$

Size of cells = $900 + 174.8 = 1074.8$, say 1050 amperes regulating rate = 1050 ampere hour cells.

Maximum booster volts on regulation when charging = $2.4 \times 292 - 550 = 151$ volts.

$$\text{Current to motor} = I_B = \frac{151 \times 400}{0.76 \times 550 + 151} = 106 \text{ amperes.}$$

Current from generator = $1100 \times (0.95) = 1045$ amperes.

Current to battery = $1045 - (400 + 106) = 539$ amperes.

Maximum booster volt amperes are $209 \times 1075 = 224.7$ K.W.

25 per cent of this capacity = 56.2 K.W., which is the size of the booster.

Maximum booster output is on charge, and is equal to 539 $\times$ 151 = 81.4 K.W.

Size of motor, basis of 85 per cent booster efficiency,

$$= \frac{81.4 \times 25\%}{0.85} = 24 \text{ K.W.}$$

Comparing now the two different equipments it is seen that the size of the battery cells is less for the high voltage than for the low, in the ratio of 1050 to 1200, or the low voltage system requires cells about 14¼ per cent larger than the high voltage equipment.

The number of cells in the high voltage equipment is greater than in the low voltage, in the ratio of 292 to 268, or 8.6 per cent Therefore the total cost of the battery on the basis of size and number of cells is less for the high voltage than for the low. This may or may not be true practically, as standard sizes of cells do not exactly fit the requirements computed for each case, and in adopting standard sizes for any service the nearest obtainable capacity is taken. Therefore, the saving, if any, depends on the relation of standards to the outputs computed. It may be considerable or it may be nothing. This question can be settled definitely only by reference to manufacturers' lists.

The capacity of motor and booster for the low voltage system is 40 + 45 = 85 K.W., while the combined capacity for the high voltage system is 56 + 24 = 80 K.W., there being a possible small saving on this item if the high voltage battery be used. Again this is a question referable to manufacturers' standards.

The regulation is better with the high than with the low voltage battery, for reasons given at the beginning of this discussion. A disadvantage of the high voltage battery is that there are 24 more cells to inspect, repair and maintain than in the low voltage equipment.

Altogether there appears but little choice between the high and low voltage batteries, the former being more suitable where the discharges are sudden, frequent and heavy, exceeding the charges in magnitude, but of short duration; while the low voltage system is the better one where the load curve is approximately of the same general form on both sides of the line of average output.

If in the diagram of connections shown in Fig. 212 the negative bus bar be connected to the earth, and the positive to the outgoing feeder switches, the complete connections for electric railway service will be shown.

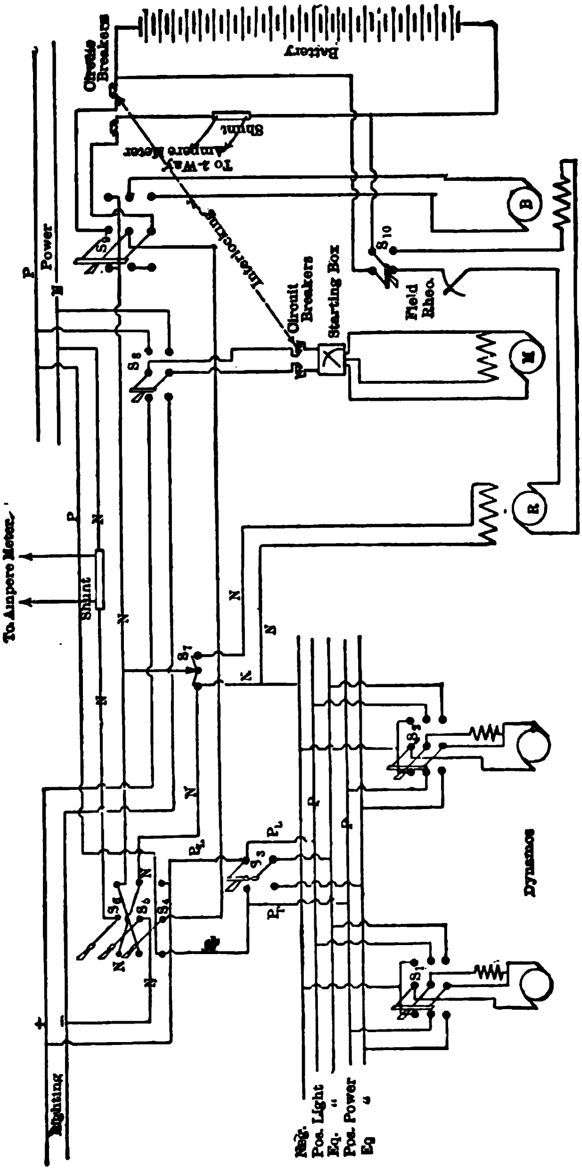


FIG. 248. Connections for Power and Lighting Station with Reversible Booster.

Fig. 248 shows the connections for large power station in which both light and power are used. The generators may be thrown on to either the light or power bus bars. The regulating booster shown is the counter electro-motive force exciter booster. In this diagram the instruments have been omitted, but they are practically the same as in the foregoing diagrams.

B is the booster, R the exciter and M the driving motor. It is to be noted that the motor and booster circuit breakers are interlocking. If the motor circuit should open, the field switch of the booster would also be opened; otherwise it would run as a motor

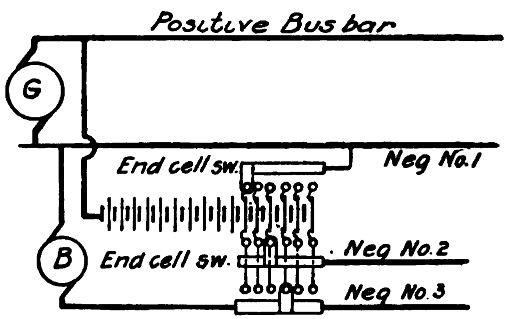


FIG. 249. Multiple Voltage System.

without excitation other than that from the armature current and speed up to destruction. The contingency in this case, however, is very remote.

The storage battery is convenient in a power station where two or three bus bar pressures are carried. Fig. 249 shows one method of accomplishing this.

The generator gives the normal bus bar voltage, and the higher voltage bus bars have cells between them and a booster in series with these added cells.

This arrangement requires one end cell switch for each voltage carried. The number of points on the bus bar switches need be only three or four, however, in cases where the feeder voltages differ by only a few volts. The booster is connected across the end cell switches carrying the highest and lowest voltages.

The voltmeter switch for every system must always be connected to points from which the voltage of the line, that of the battery, that of the booster, and the sum of the voltage of battery plus

booster may be shown without closing any switches except when reading battery plus booster.

Three-wire Systems.

Fig. 250 shows a battery connected on a three-wire system acting both as an equalizer and for power storage.

There are an end cell and a booster at each end of the system and the algebraic sum of the generator and two booster voltages is always equal to that of the battery.

The kind of boosters required depends on the character of the load. If the battery is to give regulation on fluctuating loads,

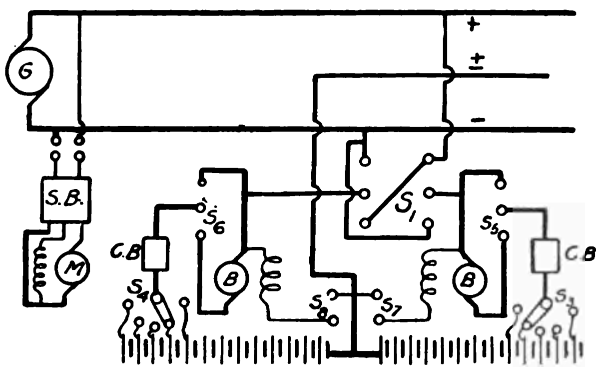


FIG. 250. Connections for Two-Booster Equalizer Battery on 3-Wire System.

some type of automatic booster which maintains the line voltage constant must be used. If the boosters are merely for charging, the ordinary shunt machine is suitable. If the boosters are used reversibly, no end cells nor end cell switches are required.

As seen in the figure, the neutral wire is connected to the middle point of the battery. This is the fixed point to which the other leads must be referred, and the individual voltages on each side are adjusted with reference to the neutral, not to the voltage across the outsides. Of course, when the voltage on each side is correct, the voltage between the outsides is also correct, but it is obvious that the voltage between outsides might be normal and yet an inequality exist between the two sides of the system.

S_5 and S_6 are single-pole, double-throw switches, by means of which the battery may be connected either to the line direct or through the booster.

S_1 is a double-pole, double-throw switch, connected as shown.

When it is closed on the lower contacts, the left-hand half of the battery is across the positive and neutral, while the right-hand half is across the neutral and the negative. If one side of the system should be more heavily loaded than the other, and therefore take more charge from its half of the battery, S_1 may be closed on the upper contacts and each half of the battery transferred to the opposite side of the system. In this way the battery discharge may be equalized, whatever the difference in requirements of the two sides of the system.

Wherever the load has an appreciable unbalance factor, S_1 should always be installed.

In this system the entire battery may be charged in series, or either half separately, and may serve as an equalizer while charging, but it cannot work in parallel with the generator during charge, unless two additional end cell switches or an automatic reversible booster be used.

S_3 and S_4 are end cell switches, M the motor, CB and CB the battery overload breakers, and SB the motor starting box.

The switches are all indicated.

The voltmeter switch connections are as follows: (1) voltage of outsides; (2) and (3) voltage of each outside to neutral; (4) voltage across battery; (5) and (6) voltage across each half of the battery; (7) voltage of outsides plus both boosters; (8) and (9) voltage of each side plus the booster on that side. When charging the total battery, at the beginning, the voltage reading (8) should exceed (4) by about 10 volts, before the switches S_5 and S_6 are closed. The charging current is afterward brought up to normal by means of the booster rheostats. While the charging takes place, the readings of (8) and (9) should be maintained equal by adjusting the booster rheostats. When charging each half of the battery separately, the sum of the line plus booster voltage should exceed that of the half of the battery by about 5 volts before closing the switch S_5 or S_6.

The circuit breakers in the battery circuit prevent the battery from discharging at a rate higher than that for which they are set.

In diagram, Fig. 251, is shown a method of connecting a battery to a three-wire system where the office of the battery is to act as an equalizer and also store energy at the time of light loads to carry the heavy peaks.

A and A are two-way amperemeters; S_1 and S_2 double-pole,

double-throw switches; CB circuit breakers; S_3, S_4, S_5, and S_6 end cell switches; R, booster field rheostat; B, the booster; M, the motor; C, the motor starting box; and S_7 and A, a switch and amperemeter, respectively, in the booster circuit. S_1 and S_2 admit

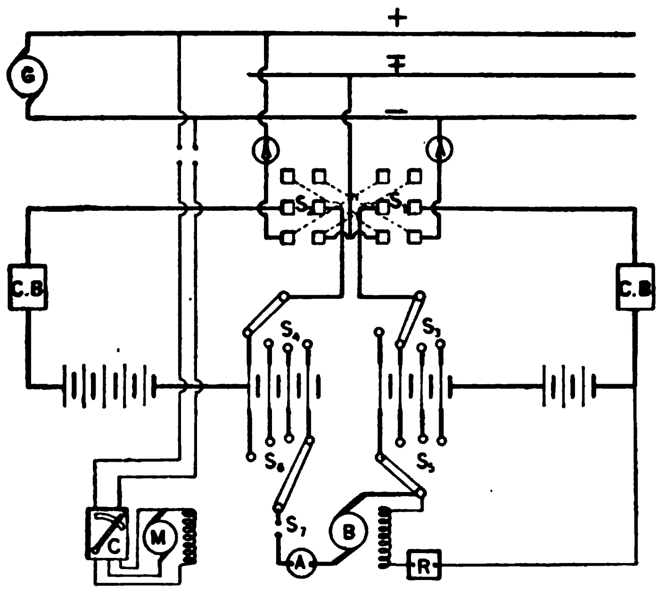


FIG. 251. Connections for Single Booster Equalizer Battery on 3-Wire System.

of changing the halves of the battery to either side of the line, as described in the preceding case.

In this system, a single booster only is used, which charges the end cells. If G is shunt-wound, the battery will partly take up fluctuations on the outside circuit, but the arrangement is not so well suited for this service as the system just before described. Also the capacity of the booster in this case must be equal to the sum of the capacities of the two boosters used in the previous case, and two end cell switches are added. Therefore, there is but little to recommend this system in comparison with the one shown in Fig. 250.

A third method of connecting on three-wire systems is that shown in Fig. 252. The two booster armatures are in series between the two halves of the battery, as shown, and the connection

to the neutral is made from the series connection between the two armatures. This is an excellent and widely used method.

The single booster system shown in Fig. 253 is a modification of diagram Fig. 251. The scheme of connection only is shown, the

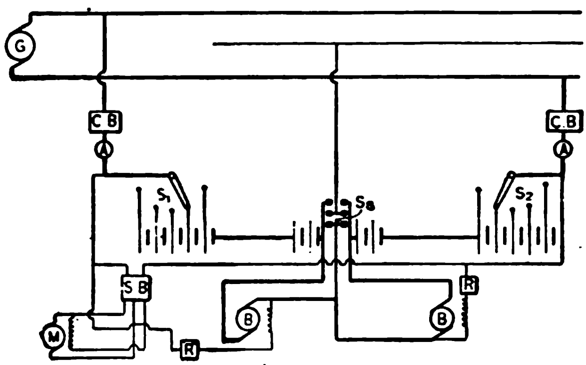


Fig. 252. Connections for Two-Booster Equalizer Battery on 3-Wire System.

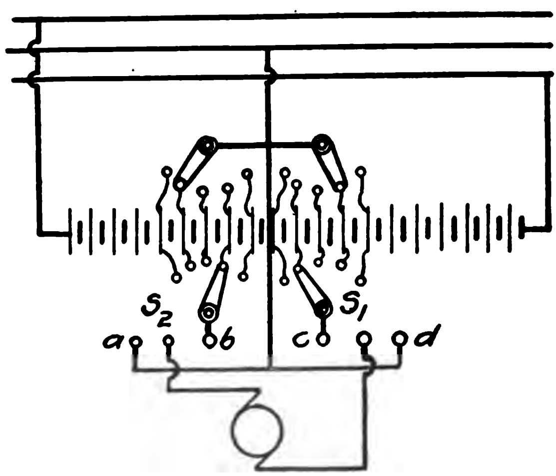


Fig. 253. Connections of Single Booster Equalizer Battery on 3-Wire System.

instruments and motor being omitted in order that the connections may be more easily followed out. The motor is connected across the outsides, and the instruments and their location are identical with those of Fig. 251. The advantage of this system over that shown in Fig. 251 is that either half of the battery may be

charged independently of the other, or the whole battery may be charged in series.

When S_1 is closed on *d* and S_2 on *b*, the booster is assisting to charge the left-hand half of the battery. When S_1 is closed on *c* and S_2 on *a*, the right-hand half is being charged, and the entire battery is charged connected across the line with the booster in series when S_1 is on *c* and S_2 on *b* When charging either half of the battery alone, care must be taken never to close S_1 or S_2 until

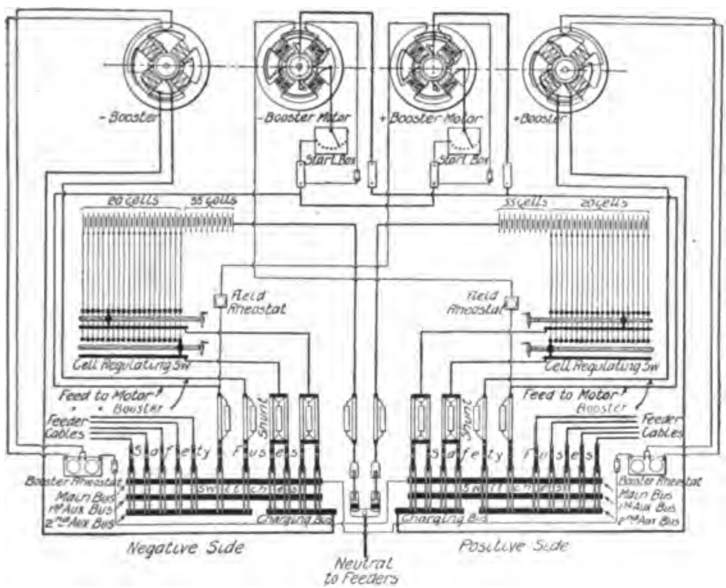


FIG. 254. Connections of Edison 3-Wire Sub-Station.

the booster has come up to voltage. If there should be no booster pressure when S_1 or S_2 is closed, the end cells included between the upper and lower contacts on which the respective arms rest would be short-circuited.

Fig. 254 shows the connections for the New York Edison Company's battery substation located in the Bowling Green Building. This station is about one mile south of the generating plant at Duane Street. The feeders run underground from the generating station to the substation, the battery receiving energy during the period of light load, and working in parallel with the generator and thereby reducing the line drop when the heavy load comes on.

The connections are obvious from the diagram. As is shown, there are three separate sets of bus bars, at different pressures, and any feeder may be connected to any bus bar. The different bus bar pressures are obtained by adjusting the end cell switches connected to them.

Fig. 255 shows the switchboard diagram for a constant-current automatic booster applied to a three-wire system. The lighting load is connected between the outsides and the neutral, while the variable load is connected across the outsides. The battery takes all the load fluctuations on the outside mains. The battery is also useful to deliver current to the lighting mains in parallel with the generators at times of heavy load. The apparatus and instruments shown are: 1 to 9 inclusive, knife switches; 10 and 11, end cell switches; 12 is a five-circuit voltmeter switch; 13 and 14, overload circuit breakers; 15, an over- and underload circuit breaker; 16, overload and no-voltage circuit breaker; 17, booster field rheostat; 18, automatic booster field regulator; 19, motor-starting switch; 20, booster armature; 21, motor; 22, voltmeter; 23 and 24 are two-way reading amperemeters, and 25 is a one-way reading amperemeter.

Any service which a battery may be made to give on two-wire systems may also be obtained on three-wire systems, and, in addition, it can be made to act as an equalizer on systems where the generators are connected across the outsides, with the single exception of the case where lighting and power are furnished from the same generators but distributed from separate sets of bus bars, the battery taking the power fluctuations. Where this case arises the only use of the battery is to take up the power fluctuations; it cannot at the same time act as an equalizer to compensate for unbalancing of the system.

It is not necessary here to give further examples of connections to three-wire systems, since any application can be made by calculating the booster and battery equipment for one side of the system as though it were an ordinary two-wire system. Doubling the equipment and placing the two halves in series across the outsides with the neutral running between them, completes the scheme of connections. In the case of the driving motors, it is in nearly every instance practicable to use only one motor to drive both boosters. This motor is invariably connected across the outsides. It is also to be remembered that the voltage between the neutral and each of

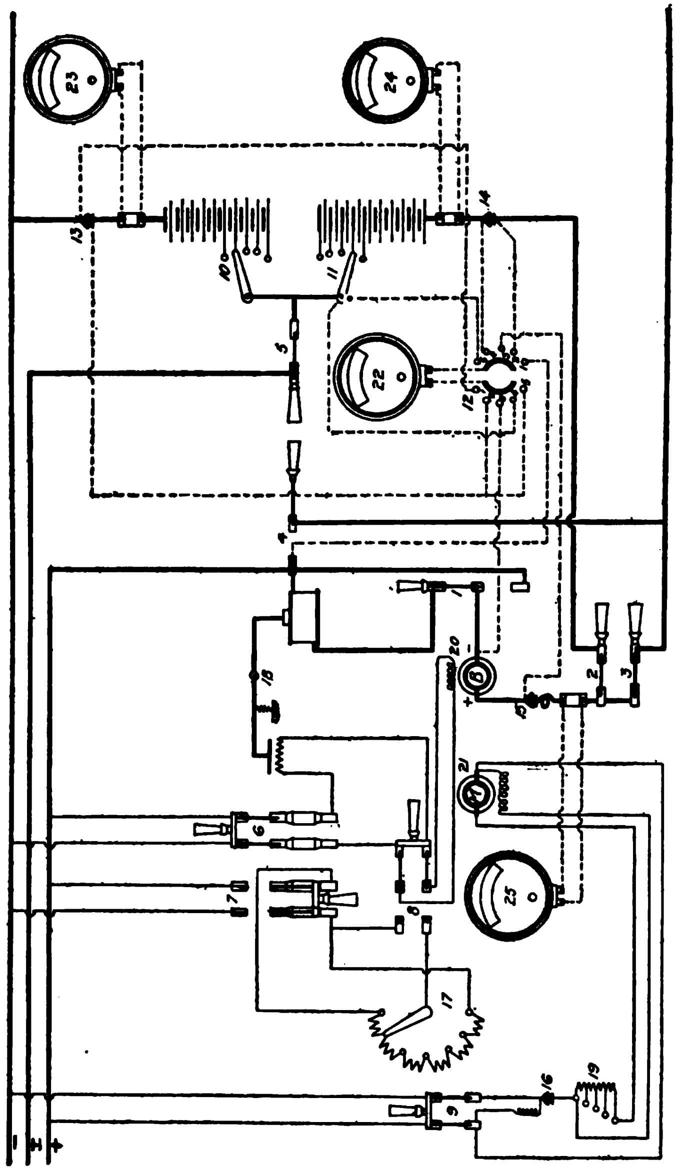


FIG. 255. Connections for 3-Wire System with Constant Current Booster.

the outsides is to be kept constant and that a maintenance of the proper voltage between outsides is not necessarily the equivalent. Therefore, all apparatus for voltage adjustment must relate to varying the potential between the neutral and the outsides and not simply the voltage across the outsides.

CHAPTER XLIII.

LINE BATTERIES.

LINE batteries are those which are connected across the feeder system or line some distance away from the generator. The voltage of the line fluctuates with fluctuating load, and the battery may simply "float," taking in current when the load is light and the line pressure high, and discharging when the load is heavy, assisting the generator and constituting a second source of current at a point where assistance is needed. In this way the voltage may be maintained reasonably constant on long lines where the maximum currents would cause voltage drops too great for operation if the copper were not greatly increased or a battery installed. The battery also tends to maintain a constant load on the station so far as the particular feeder to which it is connected is concerned, and thus bring up the economy of station operation.

Batteries may also be located at a distance from the power station and have automatic boosters connected to assist charge and discharge.

Floating Batteries.

Floating batteries work under the best possible conditions, so far as their moderate use, prolonged life and low cost of maintenance are concerned, but the maximum rates of discharge, and consequently the maximum work, cannot be secured unless the line drop is considerably greater than good service will admit. Consequently it is always better to install a booster, either at the battery or in the power station, as will later be explained.

If the battery only regulates the momentary fluctuations, and its state of charge does not materially change, a maximum variation in line voltage of about 40 volts above and below the normal, the total being 80 volts, will cause satisfactory operation and rapid rates of charge and discharge on a 500-volt railway system.

From these considerations it follows that a floating battery at the end of a long feeder may be useful for equalizing fluctuations

and keeping down the size of feeders, but not for carrying steady peaks.

Fig. 256 shows the switchboard connections of this system at the battery for electric railway service — the only service on which large enough voltage variations to make it operative can be allowed.

S_1 and S_2 are independent single-pole, single-throw switches. When S_2 is open, the battery charges only, and when S_1 is open it discharges only. The voltmeter and amperemeter, which latter is a two-way reading instrument showing charge or discharge,

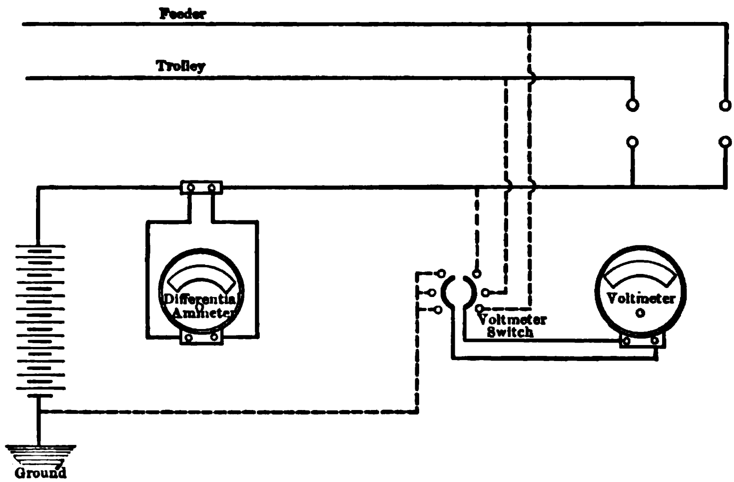


FIG. 256. Connections for Floating Battery.

are not necessary, though convenient. A remote control circuit breaker is sometimes connected between the battery and the hand switches so that the battery may be disconnected from the circuit at some distant controlling point.

The "floating" battery, as stated, depends entirely on change in line drop for its operation. For instance, if the voltage of a system be 500 volts, the line resistance to battery .5 ohm, and the average load 60 amperes, the voltage at the battery will be $500 - (.5 \times 60) = 470$ volts. If 470 volts be the open-circuit voltage of the battery, current neither discharges from it nor is charged into it when the average current is passing over the line.

If the load be decreased to say 20 amperes, the line drop is only 10 volts and the potential across the line at the battery is 490 volts, which, being 20 volts above that of the battery, will cause a charg-

ing current to flow. Conversely an increasing load will increase the line drop and lower the voltage below that of the battery, resulting in battery discharge to assist the generator, the rate of discharge being thus proportional to the load, and inversely proportional to the distance between the battery and the load.

A clearer understanding of this subject may be obtained from the following analytical discussion:

Let E_0 = generator voltage.
E_A = battery voltage on open circuit.
I_0 = current from generator.
I_x = current supply to load.
r_1 = total resistance of circuit exclusive of battery resistance.
r_x = resistance of circuit up to point of application of load.
$r_1 - r_x$ = resistance from point of application of load to battery.
R = resistance of battery (= virtual resistance).

Call the average charging current I_{AV} amperes when there is no load on the circuit. Then

$$E_0 - (I_{AV} \times r_1) = E_A + (I_{AV} \times R), \tag{210}$$

or,

$$E_A = E_0 - I_{AV}(r_1 + R). \tag{211}$$

Having determined E_A the number of cells in series is fixed and is equal to $\frac{E_A}{2.05} = N$.

The relation between I_x and I_0 is established by the following equation:

$$E_0 - I_0 r_x - (I_0 - I_x)(r_1 - r_x) = E_A + R(I_0 - I_x), \tag{212}$$

in which $I_0 - I_x$ is the current from the generator to battery at any instant. When $(I_0 - I_x)$ is negative (load greater than generator current) the battery is discharging.

Solving for I_0 in equation 212, this is found to be

$$I_0 = \frac{E_0 - E_A + I_x(R + r_1 - r_x)}{r_1 + R}, \tag{213}$$

which shows the generator current under any conditions of load or battery voltage, when the generator is compounded to give a constant pressure.

If the generator be a shunt machine another factor must be included. Take, for instance, a shunt dynamo that gives 550 volts at no load and 520 volts on full load of 150 amperes.

The maximum voltage is $E_{MAX} = 550$. The voltage at any load $= E_{MAX} - I_0h$, in which h is a constant $= \frac{E_{MAX} - E_{MIN}}{I_{MAX}}$.

Equation 213 becomes

$$I_0 = \frac{E_{MAX} - E_A + I_x(R + r_1 - r_x)}{r_1 + R + h}. \tag{214}$$

This equation shows that with a shunt machine the generator *current* variation is less than with a constant potential or compound

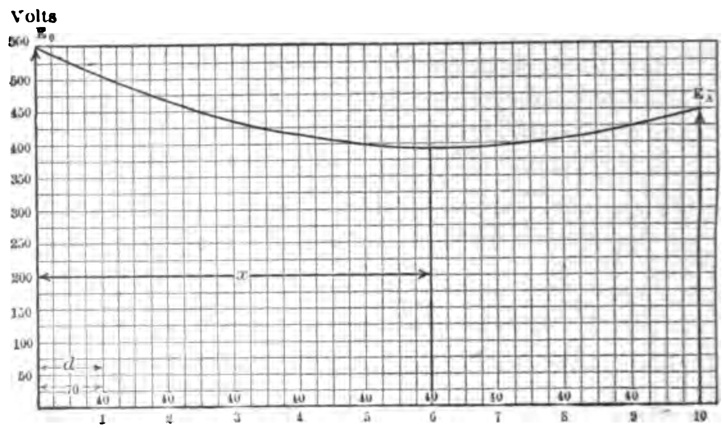


FIG. 258. Curve of Voltage on Line fed from Two Sources.

machine, but that the voltage drop is greater at the point of application of the load.

These formulæ, however, cover only the simple case of a single load between the battery and the power station. In practice, there will be usually several cars or other translating devices, between these two sources of current, and the above formulæ no longer hold. In order to compute the voltage drop and the capacity of the battery, a solution for a distributed load fed from two sources having different electro-motive forces, is necessary. This should be carefully followed, since it covers numbers of practical cases. It is also the *general case* of the division of load in a line fed from any two sources of current.

Referring to Fig. 258, E_0 and E_A are the voltages of the two sources of energy and V their difference, $= E_0 - E_A$. 1, 2, 3, 4, etc., are the points at which current is tapped off, and d is the dis-

tance apart of the taps. It is assumed that the taps are equidistantly spaced, and that the current is the same through each tap.

The current from the power station causes a drop along the line from E_0 towards the right, while from E_A the voltage falls towards the left. There is some point at which the two opposing voltages will be equal, and at this point no current will flow in the line in either direction, since the electro-motive forces are in equilibrium.

All taps to the left of this point will be fed from E_0 and all to the

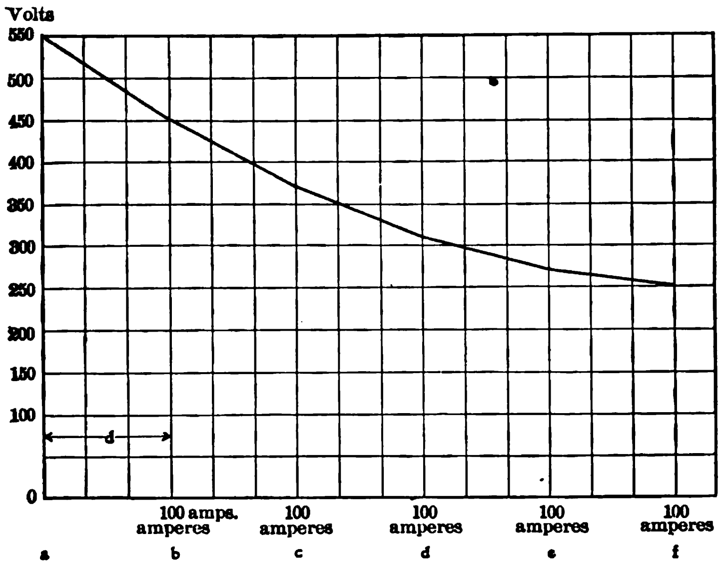


FIG. 259. Curve of Voltage on Line fed from a Single Source.

right by E_A. This condition exists at the point where $E_0 - D_0 = E_A - D_A$, in which D_0 and D_A are the drops from E_0 and E_A, respectively.

The drop from a source of supply to any point in a line which is tapped at intervals along its length, is equal to the sum of the products of the currents flowing in the line at each of the tap points between the source and the point at which the drop is to be found, multiplied by the resistance of the line from one tap to the next.

In Fig. 259, for example, if 100 amperes flow through each tap, and the resistance from one tap to the next be .2 ohm, the drop from a to b = the total amount of current flowing, multiplied by the resistance from a to b, = 500 × .2 = 100 volts. From b

to c the drop is 400 × .2 = 80 volts; from c to d = 300 × .2 = 60; from d to e, 200 × .2 = 40; and from e to f, 100 × .2 = 20 volts. The drop from a to f is = 100 + 80 + 60 + 40 + 20 = 300 volts. Of course, this could be figured from e back to a in the same way, starting with 100 amperes × .2 as the first computation.

Referring now to Fig. 258, which represents a line fed from two sources, and calling x the distance from E_0 to the point where $E_0 - D_0 = E_A - D_A$, assume that this point will fall at a point on the line which corresponds to the location of a tap. In this case, all the taps to the right will be supplied by E_A and all to the left by E_0, but the tap at which these potentials are equal will be supplied from both E_A and E_0, each furnishing one-half the amount taken.

Call a the amperes per tap, and r the resistance of the line between taps. If, for instance, the point x should fall on tap 7, the drop at 7 from E_0 would be $\frac{1}{2}ar + \frac{3}{2}ar + \frac{5}{2}ar$, etc., up to $\frac{13\,ar}{2}$, the last term being the number 13, which, in this case, is $= 7 - \frac{1}{2} = \frac{x}{d} - \frac{1}{2}$, in which d = distance between taps and $\frac{x}{d}$ is the number of taps in the length x.

The formula for D_0 = drop from E_0 to x then becomes

$$D_0 = ar\left\{\frac{1}{2} + \frac{3}{2} + \frac{5}{2} + \cdots + \left(\frac{x}{d} - \frac{1}{2}\right)\right\}. \tag{215}$$

The quantity in the brackets is an arithmetical progression in which the first term is $\frac{1}{2}$ and the last term $\left(\frac{x}{d} - \frac{1}{2}\right)$, and its sum is

$$\frac{\left\{\frac{1}{2} + \left(\frac{x}{d} - \frac{1}{2}\right)\right\}\frac{x}{d}}{2} = \frac{x^2}{2d^2}, \tag{216}$$

that is, one-half the sum of the first and last terms, multiplied by the number of terms.

$$D_0 = \frac{1}{2}ar\left(\frac{x}{d}\right)^2 \tag{217}$$

Calling L the distance between E_0 and E_A, the latter supplies current to that portion of the line which is represented by $L - x$.

In the same way as the foregoing, the drop D_A from E_A to the point $L - x$ may be shown to be

$$\frac{1}{2} ar \left(\frac{L - x}{d}\right)^2. \tag{218}$$

Since $D_0 = D_A + V$,

$$\therefore \frac{1}{2} ar \left(\frac{x}{d}\right)^2 = \frac{1}{2} ar \left(\frac{L - x}{d}\right)^2 + V, \tag{219}$$

$$\frac{x^2}{d^2} = \frac{(L - x)^2}{d^2} + \frac{2\,V}{ar},$$

$$x^2 = (L - x)^2 + \frac{2\,Vd^2}{ar},$$

$$2\,Lx = L^2 + \frac{2\,Vd^2}{ar},$$

$$x = \frac{L}{2} + \frac{Vd^2}{arL}. \tag{220}$$

That is, the distance of the point to which E_0 will feed is one-half the distance between the sources of current plus a fraction which depends for its value on the difference between E_0 and E_A, the distance apart of the taps, the current per tap, the resistance from tap to tap, and the total length from E_0 to E_A.

As an example, assume the following:

$E_0 = 550$ volts.
$E_A = 450$ volts.
$L = 40{,}000$ feet.
$d = 4000$ feet.
$a = 40$ amperes.
resistance of circuit $= .05$ ohm per 1000 feet.

$$\therefore r = \frac{4000 \times .05}{1000} = 0.2 \text{ ohm.}$$

$$V = 550 - 450 = 100.$$

$$x = \frac{40{,}000}{2} + \frac{100 \times (4000)^2}{0.2 \times 40 \times 40{,}000} = 25{,}000 \text{ feet from } E_0 \text{ and}$$

15,000 feet from E_A.

This point does not fall on a tap, but passes tap 6 and lies 1000 feet beyond and 3000 feet from tap No. 7. From the conditions of flow it is clearly impossible for the actual point of equal voltage to come between two taps, as this would mean either that two currents flow at the same time in opposite directions, or that electrical energy accumulates at some point in the wire.

In the case under discussion, the position computed simply means that E_A furnishes a portion of the current to tap No. 6, that is, the tap nearest the computed x is fed from both sources, and the current supplied by each is inversely proportional to the distance from x to tap 6, as related to the distance from tap 6 to tap 7.

The distance between 6 and 7 is 4000 feet and from x to 6 is 1000 feet. Therefore, of the 40 amperes furnished to tap 6, one-fourth, or 10 amperes, is supplied by E_A and 30 amperes from E_0. Computation of drop shows that with this distribution $D_0 = D_A + V$. It is obvious that the drops are less after transferal than those first computed, since only a small amount of current flows over the line between 6 and 7.

When the point x falls on a tap, half of the current to the tap is supplied by each of the sources. When x falls halfway between two taps, it means that no current passes over the line connecting these two taps, and the voltage distribution would be the same if the line between them were cut in two. If, for instance, x should fall halfway between 6 and 7, all current to the first six taps would come from E_0, while all to 7, 8 and 9 would be furnished by E_A, and the potential at 6 would be equal to the potential at 7. The drops would also be smaller than the computed, as no drop would be caused by the resistance from 6 to 7, since no current would flow over this part of the line.

The current supply from each source can now be determined.

From $E_0 = 40 \times 5 + 30 = 230$ and

From $E_A = 40 \times 3 + 10 = 130$.

The total current supplied $= 360$ or $= 9 \times 40$.

The voltage of the battery when neither charging nor discharging — 2.05 volts per cell — must be equal to the drop from E_0 at average load. The voltage of the battery on discharge is less than this amount by the drop due to the virtual internal resistance, and in railway work, where the changes are very quick, may be taken as .2 volt per cell.

E_A is usually taken as $2.05 - 0.2 = 1.85$ volts per cell, it being assumed that the battery keeps nearly full and is discharged at the one-hour rate on maximum load.

If x happens to fall midway between two taps — that is E_0 feeding all taps on one side of x and E_A feeding all taps on the other side — equations 217 and 218 will give results that are too small. Taking the conditions shown in Fig. 258; if x should fall midway between

taps 6 and 7, the drop D_0 would be ($ar + 2\,ar\ \ldots = 6\,ar$), the sum being

$$ar\left(\frac{1+6}{2}\right)6,$$

since $\frac{x}{d}$ is the number of taps in this case, the value of D_0 becomes

$$\left\{ar + 2\,ar + 3\,ar + \cdots \frac{x}{d}ar\right\}$$
$$= \frac{ar}{2}\left(1 + \frac{x}{d}\right)\frac{x}{d} = \frac{ar}{2}\left(\frac{x}{d} + \frac{x^2}{d^2}\right), \tag{221}$$

and D_A becomes

$$\frac{ar}{2}\left(1 + \frac{L-x}{d}\right)\left(\frac{L-x}{d}\right)$$
$$= \frac{ar}{2}\left(\frac{L-x}{d} + \frac{(L-x)^2}{d^2}\right). \tag{222}$$

The foregoing is based on the assumption that the road is level and all cars or other translating devices are using equal amounts of current, and also that they are equally distributed over the line. Where there are grades, or the distribution is unequal from any cause, there can be no general formula, since a and r vary with each case, and no series can be formed. In such cases, the method of locating x is by trial.

Assume x, and compute the drop from E_0 and to E_A, thus located. If $D_0 = D_A + V$ the point is properly located.

If $D_0 > D_A + V$, then x has been assumed too great, and another trial calculation must be made. If $D_0 < D_A + V$, x must be increased.

As an example, assume a line with the conditions as shown in Fig. 260, $E_0 = 550$, $E_A = 450$, and $V = 100$.

C_1, C_2, C_3, etc., are cars, their direction of motion being indicated by the arrows. The amperes taken and distance apart of taps are indicated in the figure.

Resistance per 1000 feet = 0.2 ohm.

Assume x to fall between C_4 and C_5. Then the drop from E_0 will be as follows:

$$0.2\,[(20 + 40 + 20)\,5 + (40 + 20)\,3 + (20)\,7] = 144 \text{ volts.}$$

The multipliers 5, 3, 7 outside the parentheses are the distances between the cars, in thousands of feet.

In the same way the drop from $E_A = 0.2\,[(10 + 40 + 35)\,4 + (40 + 35)\,3 + (35)\,5] = 148$ volts.

Since $D_0 < D_A + V$, x has been taken too small. Assume it now at the point x_2 between C_5 and C_6. $D_0 = 340$ volts. $D_A + V =$

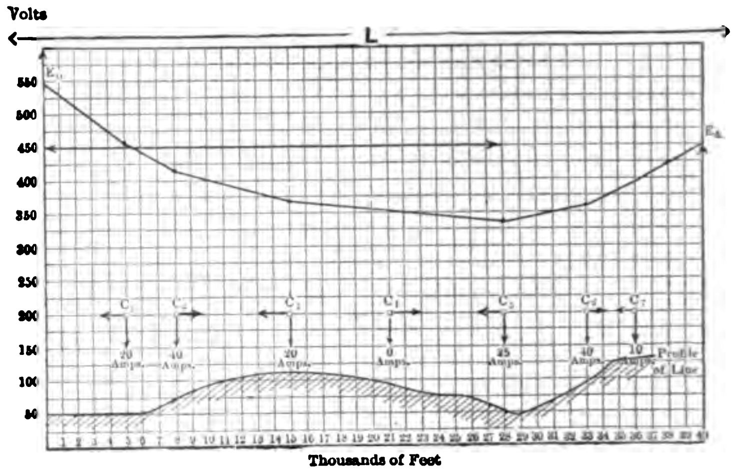


FIG. 260. Voltage and Profile of Electric Railway Line.

164, therefore x is much too great. Therefore x must fall on tap C_5, E_0 and E_A each supplying a portion of the current at that tap.

Omit the current flow to C_5 and compute the drop from E_0 to the tap nearest C_5, taking current. This point is C_3, and the drop to C_3 has been found to be 144 volts, if the current to C_5 be neglected.

Also, neglecting current to C_5, compute the drop from E_A to the tap nearest C_5 taking current. This is found to be $(50\times 4+40\times 3)\times 0.2 = 64$ volts. For D_0 and D_A to these nearest taps, the additional drop due to current supplied to C_5 must be such as to produce the relation

$$D_0 + xI_{05}r = V + D_A + r\,(L - x)\,I_{A5}, \qquad (223)$$

in which I_{05} is the current supplied to C_5 from E_0 and I_{A5} is the current supplied to C_5 from E_A. $I_{05} + I_{A5} = I_5$, or the sum of the two currents supplied from each source equals the total current to C_5.

Solving,

$$I_{A5} = \frac{D_0 + rxI_5 - V - D_A}{rL}. \qquad (224)$$

Substituting the foregoing values and taking distances in thousands of feet,

$$I_{A5} = \frac{144 + 0.2 \times 28 \times 25 - 100 - 64}{0.2 \times 40} = 15 \text{ amperes,}$$

which is the current supplied from E_A to C_5. The current from E_0 to C_5 is $25 - 15 = 10$ amperes.

A computation of the voltage drops will now show $D_0 = 200$ volts

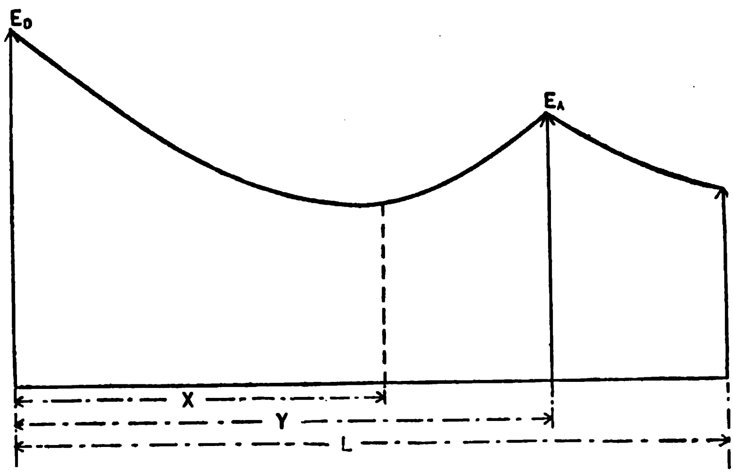


FIG. 261. Voltage of Line fed from Two Sources.

and $D_A = 100$ volts; the difference $= V = 100$ volts, which fulfills the conditions of the problem.

The practical question which usually arises is the case of a feeder or line on which the voltage drop is too great and it is desired to determine the location of the battery, its voltage and capacity. Referring to Fig. 261, L is the total length of the line, Y is the distance of the battery from the station, E_A is its voltage, and x is the point at which $D_0 = D_A + V$, as before.

It is obvious that if the resistance of the line be constant, and a minimum voltage over the line is specified, the battery will feed to an equal distance in either direction, and

$$Y - x = L - Y. \qquad (225)$$

The maximum drop on the line is specified and is equal to the drop at x, which is D_0.

From equation 217, $D_0 = \frac{1}{2} ar\left(\frac{x}{d}\right)^2$.

$$\therefore x = d\frac{\sqrt{2 D_0}}{ar}, \tag{226}$$

which locates x.

From the equation 225,

$$Y = \frac{L + x}{2}, \tag{227}$$

which locates Y.

From the condition that voltage of the generator minus the drop to x must equal the battery voltage minus its drop to x,

$$E_0 - D_0 = E_A - D_A. \quad \therefore E_A = E_0 - D_0 + D_A. \tag{228}$$

From equation 222,

$$D_A = \frac{ar}{2}\left\{\left(\frac{Y-x}{d}\right)^2 + \left(\frac{Y-x}{d}\right)\right\},$$

whence

$$E_A = E_0 - D_0 + \frac{ar}{2}\left\{\left(\frac{Y-x}{d}\right)^2 + \left(\frac{Y-x}{d}\right)\right\}. \tag{229}$$

As a practical example, assume a railway 50,000 feet long, and distance apart of cars = 5000 feet = d. There will be 10 taps on the line. Assume that each takes 30 amperes. Total current = 300 amperes.

Minimum allowable voltage at any point on the line is 350 volts.

$$D_0 = 550 - 350 = 200 \text{ volts.}$$

Resistance of line = 4 ohms.

$$\therefore r = \frac{4 \times 5000}{50,000} = .4 \text{ ohm for distance} = d.$$

$$x = 5000 \times \frac{\sqrt{2 \times 200}}{30 \times .4} = 28,810 \text{ feet.}$$

$$Y = \frac{50,000 + 28,810}{2} = 39,405 \text{ feet.}$$

$$D_A = \frac{30 \times .4}{2}\left\{\left(\frac{39,405 - 28,810}{5000}\right)^2 + \left(\frac{39,405 - 28,810}{5000}\right)\right\}.$$

$$= \frac{12}{2}\left\{\left(\frac{10,595}{5000}\right)^2 + \left(\frac{10,595}{5000}\right)\right\} = 39.4 \text{ volts.}$$

$\therefore E_A = 350 + 39.4 = 389.4$ for minimum battery voltage on maximum discharge.

The generator supplies $\frac{28{,}810}{5000} \times 30 = 173$ amperes, while the battery supplies $(10 \times 30) - 173 = 127$ amperes. Calling this the one-hour rate, the capacity of the battery should be $127 \times 2 = 254$ ampere hours.

If the exact solution of this problem is desired, it will be necessary to transfer x from the point 28,810 feet, which falls 3810 feet beyond the fifth tap and within 1190 feet of the sixth, to the sixth tap by the method previously given.

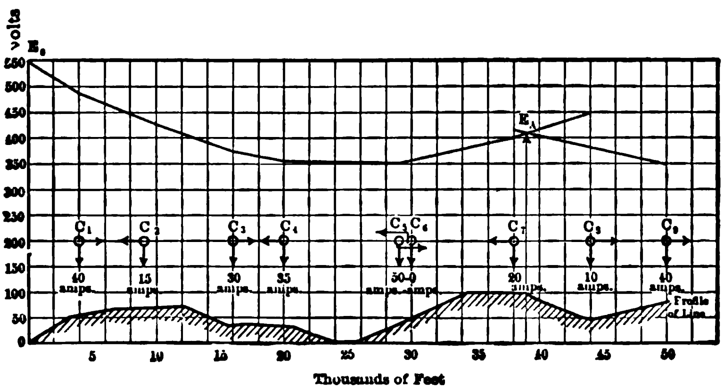


FIG. 262. Profile and Voltage of Line of Railway fed from Two Sources.

This transfer will change the location of Y, which should, when possible, be placed at a tap point, or in case of moving cars, placed in such a position as to be near or at the point passed by a car when maximum current is drawn from the line.

As a practical example of location on a line with grades and the determination of the proper voltage and capacity of a battery, the conditions shown in Fig. 262 may be assumed.

$E_0 = 550$, r per 1000 feet $= 0.125$ ohm. Maximum voltage drop $= 200$ volts.

From inspection, assume x to be at C_5 and that one-half the current to C_5 is delivered from each source.

The drop from E_0 supplying 25 amperes to C_5 is 275 volts, which is greater than the permissible drop. Now assume E_0 to feed up to C_4 and supply all the current thereto. The drop to C_4 is found to be

183.4 volts. This is 16.6 volts less than the permissible drop, and some current will be furnished to C_5 by E_0, the amount being equal to

$$\frac{16.6}{0.125 \times 29} = 4.6 \text{ amperes,}$$

29 being the thousands of feet from E_0 to x.

Starting from C_5 at the voltage 350 (= 550 − 200), and working towards the right, the curve of drop towards Y is plotted, it being remembered that current to C_5 from E_A is 50 − 4.6 = 45.4 amperes; and beginning at C_9 and working towards the left, the curve of drop to Y is plotted. The intersection of these curves locates Y and gives the value of E_A.

In this case, the intersection falls at point 10,100 feet from C_5 and 10,900 feet from C_9, and the voltage E_A is 420 volts. This corresponds to 227 cells at a minimum voltage of 1.85. The floating voltage is 227 × 2.05 = 465 volts. If this is greater than the average voltage of the line at the point where the battery is located, a booster must be installed, which will take up the loss in battery voltage on discharge. As a matter of fact the line voltage with all load removed would be only 550 volts less the drop due to current supply to battery, and as the resistance from generator to battery is about 5 ohms, it is obvious that the 227 cells would receive little or no charge. The conditions, therefore, make it impracticable to use a floating battery unless some means of increasing the station voltage for charge be available. If a booster were installed, the number of cells required would be $\frac{420}{2.05} = 205$ cells.

In some cases, the discharge from the battery will be greater or less than the amount of charge it receives from the line, depending on whether E_A is above or below the voltage of the line at the battery on average load. If less, the number of cells should be increased to bring E_A up to the average voltage. If greater, the only help is a constant-current booster, or more feeder copper, or both. If it is not objectionable to raise the voltage of the feeder, the booster may be put in series with it, the added voltage being just enough to make the line voltage at the battery equal to E_A on average load, and the carrying capacity of the booster must be equal to the average line load. In some cases it may be necessary to run an auxiliary feeder to the battery, the constant-current booster being in series with it. The carrying capacity of the

feeder and booster must be such as to deliver continuously a current equal to the *average* difference between the amount of current put into the battery by the line, and its discharge.

The voltage must be just sufficient to cause this amount of current to flow through the auxiliary feeder into the battery on average load. If it is higher, the line will be partly fed from the auxiliary feeder and the battery will not do its share of the work, and the I^2R loss in the feeder will be increased owing to the increase in current through it.

Consider now the question of difference in cost between the battery and a sufficient amount of copper to effect the same result, and take, as a concrete example, the case shown in Fig. 262. Take the track resistance as equal to .015 ohm per 1000 feet. The resistance total per 1000 feet is 0.125, making the feeder resistance .11 ohm per 1000 feet, corresponding to about a No. 0 hard-drawn copper wire with splices. While this is somewhat small for the maximum current carried, it does not affect the result as to increased copper required to maintain the voltage. It is also quite large enough for the current it carries with a battery on the line, since the greatest current is that from E_0 to C_5, which at maximum load is 124.6 amperes.

The drop computed on a basis of 0.125 ohm per 1000 feet is 767 volts at the end of the line, or far more than the generator voltage. If the drop is to be 200 volts, the resistance of the line must be equal to $\frac{200 \times .125}{767} = .03265$ ohm per 1000 feet.

The resistance of the track being .015, the copper resistance must be $.03265 - .015 = .01765$ ohm per 1000 feet, which corresponds to about 610,000 circular mils. The cross section of the trolley wire in place is 105,500 circular mils.

The additional copper required, then, is $610{,}000 - 105{,}500 = 504{,}500$, say 500,000 circular mils. Taking the cost of copper erected as 18 cents per pound, including additional cross arms, insulators, labor, etc., the cost of this copper would be about $14,200.

The cost of the battery would be as follows:

227 cells of 230 ampere hours capacity at $14.00	$3,178.00
Switchboard	220.00
Erection	380.00
	$3,778.00

The large feeder would reduce the I^2R loss below that of the smaller one — which latter is sufficiently large if the battery be installed, but the economy effected by the latter in steadying the load on the power station will much more than counterbalance this saving in I^2R loss.

The floating battery has the advantage of simplicity, and acts instantaneously, as it has no time lag, which is always present in a booster, as the latter depends on changes in its magnetization to effect changes in voltage. The variation in voltage required and the

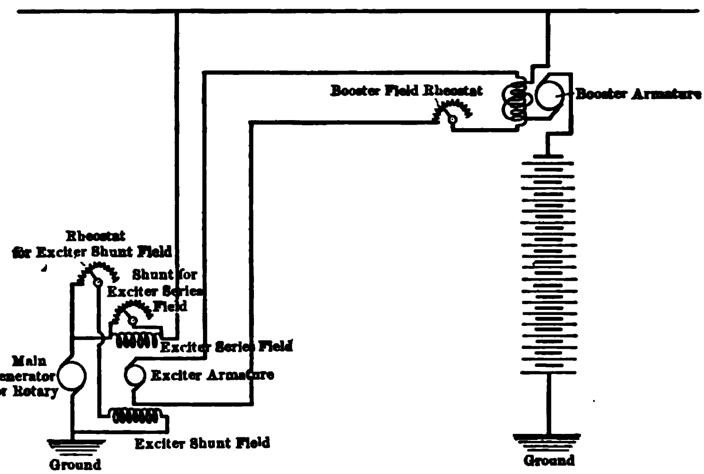


FIG. 263. Booster and Battery at Distance from Station, Exciter in Station.

fluctuation in generator load are, however, too great to admit of successful operation on any but a railway or power circuit, and generally, a proper booster would help the regulation greatly.

Booster-controlled Line Batteries.

As has before been pointed out, fewer cells are required, their size may be less, and the regulation improved if line batteries are controlled by automatic boosters instead of depending on voltage changes in the line itself for causing charge and discharge.

There are several methods of arranging boosters for this service. Of course, a reversible booster can be installed at the point where the battery is located, but the objection to operating commutating, dynamo-electric machinery without attendance makes this arrangement unsuitable except in the case of large substations.

One method of placing the booster at the battery that has been successfully used is indicated in Fig. 263.

The booster, which is a separately excited machine, is placed in the battery substation, while the exciter is placed in the main station. No special feeder is necessary from the main station to the substation, only the two exciter wires which carry but a few amperes — from 4 to 6 amperes with a 50-K.W. compensated booster.

In this case, the exciter has a shunt coil as well as the usual series winding, the two being in opposition. The resultant magnetization is zero at normal load, changing up or down with variation of load,

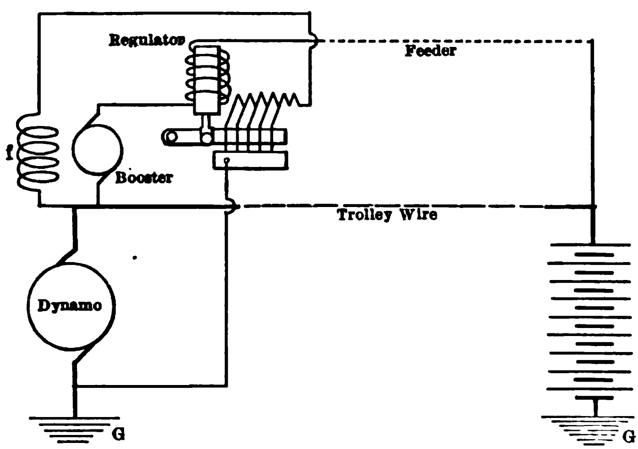


FIG. 264. Connections for Line Battery with Station Booster.

correspondingly changing the current in the exciter field, both in direction and intensity. The net result, of course, is to produce a booster voltage of such magnitude and in such a direction as will cause the battery to meet the load changes.

The booster is provided with a few series turns in addition to the regulating exciter coil. The series coil produces always an excitation which opposes that of the externally excited coil. The object of this opposing series winding is to limit the battery discharge or charge when the load changes greatly from the normal. In such cases, the generator must work at an overload or underload rate for the time during which the excessive load or very slight load may last.

This limiting effect can be produced by winding booster to work up to the knee of the magnetization curve, and when this limit is reached the voltage will not increase proportionally to the load.

The location of the battery and the booster is determined in the same manner as the location of a floating battery. The better practice, except in special cases, is to install the booster in the power station. This method requires the use of a non-reversible booster, and unless the line voltage at the station can be raised about ten per cent, a special feeder from the station to the battery must also be put in.

Fig. 264 shows a diagram of connections for an externally controlled, non-reversible booster in the power station, regulating a

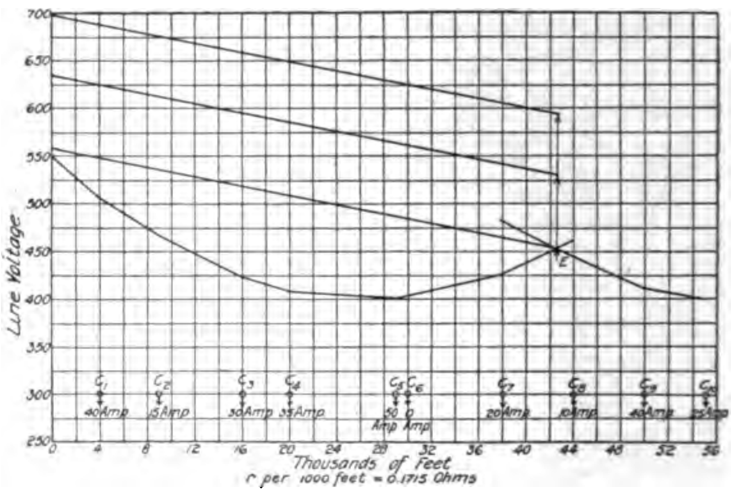


FIG. 265. Loadings and Line Voltage of Railway fed from Two Sources.

distant battery through a special feeder. To bring out clearly the methods of computation for this system, the following example is given.

Generator voltage, normal, 550 volts.

Length of line and loadings as given in Fig. 265.

Minimum voltage on line for these loadings, 400 volts.

Then generator can feed out to such a point as will give a feeder drop of $550 - 400 = 150$ volts. Assume that the trolley wire is No. 00 B. and S. gauge and that there is no feeder in parallel with it. Resistance per 1000 feet of copper $= 0.08$ ohm. Take the track resistance as 0.0054 ohm per 1000 feet, which corresponds to the resistance of a well-bonded, single-track road laid with 70-lb. rails. Total

resistance of 1000 feet of circuit is $0.08 + 0.0054 = 0.0854$ ohm. The product of amperes × thousands of feet through which the generator will feed with a 150-volt drop $= \frac{150}{0.0854} = 1756$ thousands of ampere feet, which will be denominated M.A.F.

Products of the amperes × thousands of feet for the several cars are of

$C_1 = 40 \times 4 = 160$; $C_2 = 15 \times 9 = 135$; $C_3 = 30 \times 16 = 480$;
$C_4 = 35 \times 20 = 700$; $C_5 = 50 \times 29 = 1450$; $C_6 = 0 \times 30 = 0$.

By inspection the generator will feed out to C_4. Total M.A.F. to $C_4 = 160 + 135 + 480 + 700 = 1475$. This is a less number of M.A.F. than the 1756 computed, from which it is seen that the generator feeds to C_4 and also delivers some current to C_5.

M.A.F. for $C_5 = 1756 - 1475 = 281$. Amperes to $C_5 = \frac{281}{29} =$ 9.7 amperes, the factor 29 being the distance in thousands of feet from the generator to C_5.

Curve No. 1 shows the drop from station to C_5. Starting from C_5 and working outwards, away from the power station, plot the curve of voltage drop upwards, thus:

Current to C_5 from battery $= 50 - 9.7 = 40.3$ amperes.

Distance from C_5 to $C_7 = 9$ thousand feet. (C_6 omitted because current is zero.) Drop from C_7 to $C_5 = 40.3 \times 9 \times 0.0854 = 31$ volts.

The potential at C_7 then is $400 + 31 = 431$ volts

Distance from C_7 to $C_8 = 6$ thousand feet.

Drop from C_7 to $C_8 = 40.3 + 20$ amperes $\times 6 \times 0.0854 = 31$ volts.

The voltage at C_8 then must be 31 volts greater than at C_7 and its voltage therefore $= 431 + 31 = 462$.

Begin now at C_{11}, taking it as 400 volts, and in a similar fashion work back to C_8, at which point the voltage will be 482.5 volts.

Curves 3 and 4 show the curves of drop from C_9 to C_5 and from C_8 to C_{11} respectively. Their intersection shows the point at which the battery should be located, and the elevation of this intersection shows the voltage of the battery when discharging its maximum current. This point is located 42,450 feet from the station and $56{,}000 - 42{,}450 = 13{,}550$ feet from the end of the line.

The voltage of the battery is 452 volts. If this is the pressure

when discharging and the volts per cell are 1.75, the number of cells $= \frac{452}{1.75} = 258.$

Volts when floating on line = 2.05 × 258 = 530 volts.

Volts on charge up to 2.3 volts per cell = 2.3 × 258 = 594 volts.

Maximum current supplied by the battery is 40.3 amperes to C_6, and all the current from C_7 to C_{10} inclusive = 145.3 amperes.

If this is twice the average load, the booster in the station must supply continuously 73 amperes over a special feeder. To determine the drop allowable in the feeder, the continuous loss plus the interest on the copper must be equated against the cost of current and interest on the cost of the booster, and the booster voltage obviously increases with the volts drop in the feeder.

Assume this quantity to be computed and the most economical drop found to be 105 volts.

Resistance of feeder $= \frac{105}{73} = 1.44$ ohms.

Length of feeder = 42,450 feet.

Resistance per 1000 feet $= \frac{1.44}{42.45} = 0.034$ ohm, corresponding to a 300,000 cm. cable.

Its weight will be 920 lbs per 1000 feet, and it will cost around 18 cents per lb. erected, or $165.60 per 1000 feet, the total cost being $7029

The booster will have to give a maximum voltage of 594 + 105 − 550 = 149, say 150 volts, and its size will be 150 × 73 = 10.95 K.W. The battery overcharge will be with say 35 amperes, when practically all load is off the line, the drop being 35 × 1.44 = 50.5 volts, so that the charging voltage will be 550 + 150 − 50.5 = 649.5 volts, which is $\frac{649.5}{258} = 2.55$ volts per cell. To obtain a "boiling" voltage of 2.6 volts per cell the generator voltage will have to be raised about 12 volts, unless the booster be made to give 163 volts maximum. In this latter case its capacity will be 163 × 73 = 12 K.W.

The normal booster voltage will be 530 + 105 − 550 = 85 volts.

Size of motor $= \frac{73 \times 85}{.86\%} = 7.2$ K.W. .86 being the assumed efficiency of the booster.

The booster voltage at the time of battery discharge will be

$452 + 105 - 550 = 7$ volts. The pressure at E will obviously rise and fall with the changes in load on the system. The current in the feeder, and therefore the drop through it, will be constant, the booster voltage rising and falling with the voltage at E. In the figure the straight lines from E to the left end of the figure and making an angle with the horizontal, represent the drop in the feeder and the pressures at its two ends, for the three conditions of battery charge, floating, and discharge. The distance of the left end of each of these lines above the generator voltage shows the voltage of the booster.

Although the battery voltage rises above that of the generator, there will be no discharge to the station, as the track between the battery and the station will always have some load on it, and any attempt of the battery to feed back to the station would be followed by a diminution of battery voltage which would drop until some point of equilibrium would be reached at which the generator voltage − drop = battery voltage − drop.

Cost of motor and booster with automatic regulator will be approximately $800.00, installed. Battery cells, to give a discharge of $145.5 - 73 = 72$ amperes. If this is the 1-hour rate, the size of the battery is $2 \times 72 = 144$ ampere hours. Cells of this size are very small and would have no reserve capacity; 250-ampere-hour cells should therefore be adopted. The cost of the battery installed would be about $3600.00. The total cost, therefore, would be $11,429.00, to maintain the voltage within a minimum of 400 volts over a line 10 miles long and regulate a portion of the load.

If the minimum current to the line is one-third that of the maximum, the output of the generator, without the battery in service, will fluctuate between 92 and 275 amperes. With the battery, the fluctuation will be between $92 + 73$ and $275 - 72$ or between 165 and 203 amperes, which is reasonably constant, and the reduction in the amplitude of the fluctuations will result in more economical operation of the steam plant.

If a feeder were put in without a booster and of such area as to give a drop of 98 volts when 143.5 amperes flow through it, and running from the station to a feed point located in the same place as the battery, its resistance would be $\frac{98}{143.5} = 0.682$ ohm.

$$\text{Resistance per 1000 feet} = \frac{0.682}{42.45} = 0.0161 \text{ ohm.}$$

This corresponds to a 650,000 cm. cable weighing 1990 lbs. per 1000 feet. At a cost of 18 cents per lb. erected, this feeder would require the investment of $1990 \times 0.18 \times 42.45 = \$15,205.00$, which is \$3776.00 more than the cost of battery booster and feeder when the battery is installed.

The losses in the large feeder are less than the small one carrying a constant load, but this advantage is more than offset by the better regulation obtained by use of the battery and consequent saving at the station. Also with the battery, the cars C_7 to C_{10} inclusive could be operated for more than an hour in case of an accident or breakdown. If the voltage to be maintained were higher than 400, say 450 volts, the saving of the battery and auxiliary equipment over the cost of a large feeder will be still greater than in the case above computed.

To find the maximum current required for a railway at any time, a train sheet should be laid out, in the usual form, with the distances as ordinates and the abscissæ representing time, diagonal lines showing the location of any car or train at any time. By inspection, concentrations of load can be located, and by taking a number of intervals separated by a few minutes only, and assigning to each car the current required at the instant taken, curves of current consumption, both total and for any given section of the road, may be plotted.

To facilitate the computation a profile of the road should be laid out on the same sheet, running parallel to the ordinates. The train sheet should be laid out to a large scale if there are many grades in the road. Particular attention must be paid to starting cars, and the current consumption of the whole system or section computed for the instant of each start.

Three-wire Substations.

Large direct-current, three-wire distributing systems usually have a storage battery substation at some point near the end of a heavily loaded line, and although these stations have boosters, end cell switches and other apparatus in them and are looked after by regular attendants, they may be termed line batteries.

A diagram of connections and a description of an installation of this kind are given in Chapter XLIII.

CHAPTER XLIV.

PLANT EFFICIENCY.

THE efficiency of batteries on storage and regulation service has been previously treated in Part I, Chapter XII. The addition of boosters, of course, lowers the efficiency somewhat, but not so much as might be at first supposed.

Consider first a case of regulation on a system supplying fluctuating load, such as is shown in Fig. 267.

The average load to be furnished by the generator is 605 amperes and is indicated by the horizontal dotted line. The readings are taken at intervals of five seconds. The battery is to absorb all the excess current when the external load falls below the 605 amperes line, and deliver all current required above this amount.

As has been shown in Chapter XXXV the maximum motor current at the time of maximum discharge and minimum battery voltage is approximately 33⅓ per cent of the battery current to the line. On this basis, the maximum battery current is 300 + 100 = 400 amperes. The booster must therefore pass this current, and if the normal current rating of the booster be 25 per cent of this, 100 amperes will be its rated carrying capacity. This assumes an interpole or compensated winding booster.

The battery being for regulation only, the number of cells $= \frac{E_0}{2.05}$, it being assumed that a booster in series with the battery will be used, the voltage of which is zero at normal load. In this case, the voltage of the system is 220, and the number of cells, therefore, $\frac{220}{2.05} = 107$. The maximum voltage of this battery when being overcharged, is $107 \times 2.6 = 278$ volts, of which $278 - 220 = 58$ volts must be furnished by the booster. Rating of booster is therefore $58 \times 100 = 5.8$, or say 6 K.W.

The maximum continuous booster output is when overcharging the battery at the 8-hour rate. Since the regulating rate of the battery is 400 amperes, its capacity is 400 ampere hours, and the

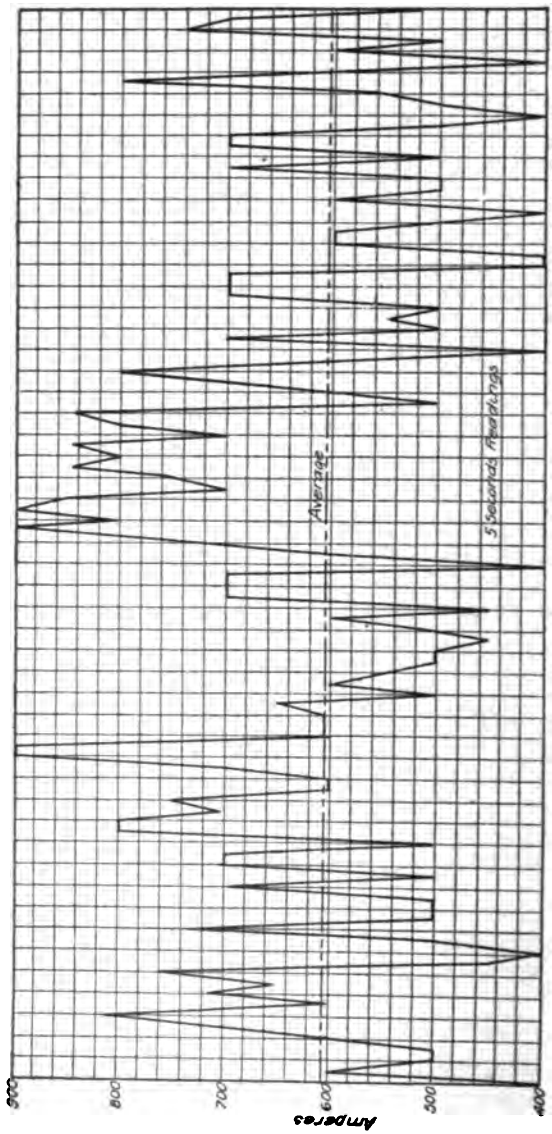


Fig. 267. Curve of Fluctuating Load.

current rate for 8 hours = 50 amperes × 58 = 2.9 K.W., which is the booster output on battery charge.

The maximum output on regulation is when the battery voltage has fallen to 1.65 volts per cell and the maximum discharge of 300 amperes to the line and 100 amperes to the motor, or total of 400 amperes, is delivered by the battery. Booster pressure = $220 - (1.65 \times 107) = 43.5$ volts. Booster output = $400 \times 43.5 =$ 17.4 K.W. The motor output for this load $= \frac{17.4}{0.86} = 20.2$ K.W, 0.86 being the booster efficiency.

If an interpole or compensated motor be used, a normal rating of 25 per cent of the maximum, or 5.05, say 5 K.W., may be used.

If the efficiencies of motor and booster are each 86 per cent at full load, the losses will be 14 per cent, divided as follows:

3% friction and windage.
4% iron loss.
4% copper loss in fields.
3% copper loss in armature.

The constant loss for the booster is simply friction, or 4 per cent, which is $0.04 \times 6 = 240$ watts. The constant loss for the motor is the sum of all the losses except the armature copper loss, and is $0.11 \times 5 = 550$ watts.

From the load curve it may be found that the average booster discharge throughout the time over which it extends is 22 amperes. The average charge is likewise 22 amperes, making the equivalent of 44 amperes plus the motor current flowing continuously through the booster. Remembering that this 44 amperes is made up of both charge and discharge currents, the booster voltage is proportional to an average charge or discharge of 22 amperes. The virtual resistance of the battery is about 0.0625 ohm, so that the average booster volts are only $22 \times 0.0625 = 1.375$ volts. Therefore the motor current to supply booster energy is negligible. The iron loss in the booster is proportional to its $(\text{voltage})^{1.6}$ and for 58 volts = 4% of 6 K.W. = 240 watts. For less than 2 volts this loss would be less than 1.2 watts, which is also negligible. The armature loss is proportional to the $(\text{current})^2$ and for 100 amperes = 3% of 6 K.W. = 180 watts. Loss for 44 amperes $= \frac{(44)^2}{(100)^2} \times 180 =$ 34.8 watts. Copper loss in fields is proportional to the $(\text{voltage})^2$. For less than 2 volts this loss is negligible.

Loss through regulator (assumed), 140 watts.

Total average losses then are 240 + 550 + 34.8 + 140 = 964.8, say 965 watts.

The average voltage of charge being 220 + 1.375 = 221.375 volts and the time covered by the curve being 1000 seconds, the energy taken from the battery is 22,000 ampere seconds = 22,000 × 221.375 = 4870 K.W. seconds. Assuming the battery efficiency on regulation to be 92%, the loss in the battery is

$$.08 \times 4870 = 389.6 \text{ K.W. seconds.}$$

Summing up the losses:

Booster, motor and regulator = 965 × 1000 =	965 K.W. secs.
Battery	389.6 K.W. secs.
The total being	1354.6 K.W. secs.

The total energy delivered to the line from the battery is 487 K.W. seconds, and the total energy taken from the system for battery charge is 4870 + 1354.6 = 6225.6 K.W. seconds. Efficiency of battery equipment is therefore $\frac{4870}{6224.6}$ = 78 per cent. This figure, however, gives no conception of the effect on the station, which, after all, is the *crux* of the discussion.

The total output of the plant during the period covered by the curve was 605,000 ampere seconds, or 605,000 × 220 = 133,100 K.W. seconds. The losses were 1355 K.W. seconds and total energy generated was 133,100 + 1355 = 134,455 K.W. seconds. $\frac{133,100}{134,455}$ = 99.2 per cent plant efficiency.

For a loss of 0.8 of one per cent of the total energy generated, fluctuations which vary as much as 50 per cent of the average output have been taken off the engines and dynamos with a consequent saving of from 10 to 20 per cent in fuel consumption. The battery, motor and booster losses are therefore negligible as compared with the total load steadied and the saving resulting therefrom. The steam consumption of engines working at a steady rate is much less than when supplying a fluctuating load, if the horsepower hours for a given length of time be the same in either case. The saving due to working at a constant output is greater with reciprocating engines than with steam turbines, the steam consumption curve of the latter type of prime mover being much flatter than the corresponding curve for reciprocating engines. In

certain types of single-valve, high-speed engines, the steam consumption per horse-power hour, on a load fluctuating between zero and 125 per cent of the normal rated output of the engine, the average load being about 75 per cent of the engine rating, will be 70 to 80 per cent greater than if the same engine worked constantly at the 70 per cent load.

In order to settle the question of saving, a curve of steam consumption at various loads such as is shown in Fig. 268 must be

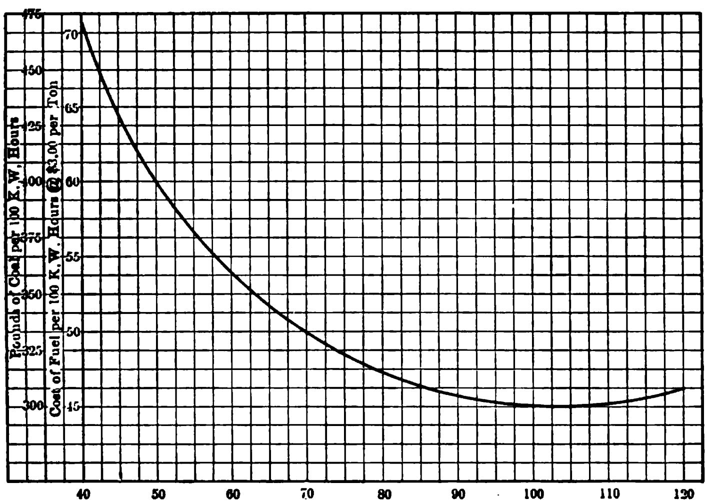


FIG. 268. Curve showing Variation in Steam Consumption of Engine with Load Changes.

plotted. From the curve of fluctuating load take points, and from these plot another curve having the same abscissæ as the load curve, the ordinates being equal to the steam consumption per horse-power hour for the particular value of load at the point taken multiplied by the number of horse-powers indicated at that point. The average of the resulting curve will be the steam consumption of the engine for the fluctuating load.

The curve of steam consumption per horse-power hour must be for delivered electrical power and not simply indicated horse power.

In the case of equipments to carry load peaks, the computations do not show so marked an advantage, and indeed there are many

cases where it is more economical to carry the peaks with generating machinery if the sole office of the battery is to handle these excess loads, and the features of reliability, equalizing, maintenance of constant bus bar voltage and the other advantages which go to make a battery of value in a station, be neglected.

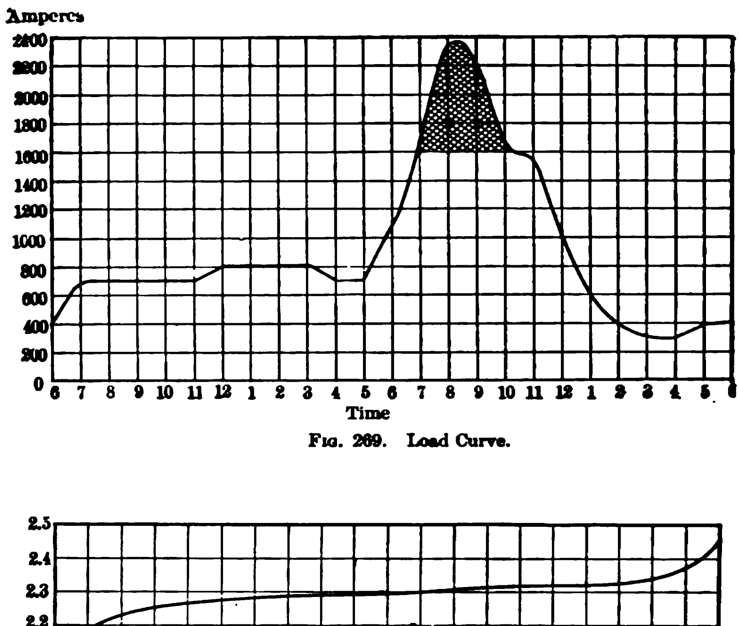


FIG. 269. Load Curve.

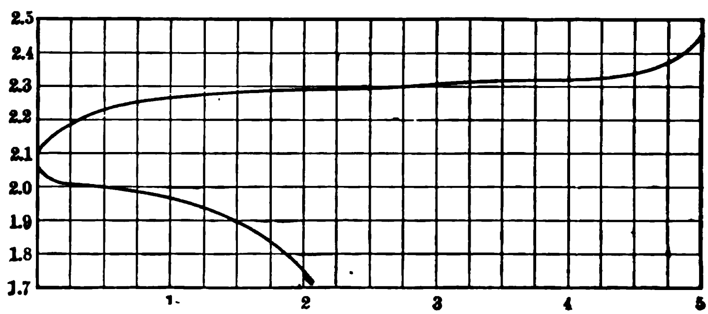


FIG. 270. Curves of Battery Charge and Discharge.

Consider a plant working on 110 volts, having a load curve such as that shown in Fig. 269 and equipped with generating machinery to carry 1600 amperes. The peak rising above 1600 and shown by the cross-hatched area and representing 1530 ampere hours, is to be carried by a battery of 61 cells.

From the charge and discharge curves shown in Fig. 270, which are for the 5-hour rate of charge and 2-hour rate of discharge, it is

found that the average voltage of charge is 2.29 and that of discharge 1.93 for the particular cell from which the curves are taken.

The ampere hour efficiency may be taken as about 90 per cent. Then $\frac{1530}{0.90} = 1700$ = ampere hours of charge. The voltage added to this charge by the booster is 61 $(2.29 - 1.93) = 22$ volts.

$22 \times 1700 = 59.4$ K.W. hours added by booster.

Assuming the motor and booster efficiencies as 88 per cent each for machines as large as these, the combined efficiency is 77.5 per cent. The energy taken from the switchboard by the booster motor is

$$\frac{59.4}{.775} = 76.5 \text{ K.W. hours.}$$

The total energy taken from the switchboard, then, is $76.5 + (1700 \times 110) = 263.5$ K.W. hours.

The battery puts back into the line

$$1530 \times 1.93 \times 61 = 180 \text{ K.W. hours,}$$

and the loss is 83.5 K.W. hours.

The efficiency of the battery equipment then is $\frac{180}{263.5} = 68.3$ per cent.

The total station output is 22,430 ampere hours, which, at 110 volts = 2467 K.W. hours.

The total energy generated is $2467 + 83.5 = 2550.5$ K.W. hours.

Efficiency of plant $= \frac{2467}{2550.5} = 96.8$ per cent. Loss = 3.2 per cent of total daily output.

Assume the efficiency of the engine and generator to be 90 per cent each. The combined efficiency = 81 per cent. Then 180 K.W. hours at the switchboard $= \frac{180 \times 1.34}{0.80} = 298$ cylinder or indicated H.P. required, and the 263.5 K.W. used in charging the battery = 435 indicated H.P. $\frac{435}{298} = 1.46$. Therefore, for each horse power which the battery discharges on the peak, 1.46 indicated H.P. must be developed in the cylinder, or nearly 50 per cent excess.

As to whether this increased power can be produced at a less cost at certain periods of load than the amount discharged into the line

can be at the time of heavy loads, depends on the type of station, its steam and generating equipment, and the character of the load. As has been stated, the change in steam consumption with change in load is comparatively small for steam turbines. Fig. 268 is a typical curve for high-speed, reciprocating engines.

From this curve, it is seen that the fuel consumption per H.P. hour increases rapidly as the load decreases. This curve is not applicable to any general case, but varies for each particular station. If the unit be of 250 K.W. normal capacity and is working at the 100 K.W. rate, it is costing 70 cents per hour for fuel at this 40 per cent load. If the 146 H.P., before computed, be added to the generator load to charge the battery, the total load will be $100 + 146 = 246$ H.P., or practically full load. Cost of fuel per hour $= 246 \times 45 = \$1.10$. The additional fuel cost to charge the battery then is $\$1.10 - 70 = 40$. The battery will give out 100 K.W. hours for the 146 charged into it. If, at the time of the peak, the whole plant were run at full load, it would cost 45 cents to generate the 100 K.W. hours. This shows a saving of 5 cents, or 11 per cent, in fuel by using the battery to carry the peak of the load. If the plant were not running on full load the saving would be still greater. Also, if the boiler capacity of the plant is smaller than it should be for handling the peak, the saving in favor of the battery will still further be increased.

On the other hand, if at light load the units at work are delivering an output near their full load capacity and to charge the battery another unit would have to be started up which would not be fully loaded by the battery, and the generating and steam equipment is properly proportioned to handle the peaks, then the installation of a battery for the sole purpose of handling the heavy load would result in a positive loss.

It therefore depends entirely on the character of the station and its equipment, whether or not a battery is the most economical apparatus to take care of a steady overload.

In most stations, however, the regulating effect and guarantee against breakdowns are the chief factors which influence the installation of a battery plant.

CHAPTER XLV.

EXCITER BATTERY INSTALLATIONS.

ONE of the principal uses of storage batteries is to act as a reserve source of excitation for alternating-current generators in large power stations. The battery is connected across the exciter bus bars and, therefore, is always in parallel with the exciting generators. The battery does no work, and, normally, does not either receive current from or deliver it to the bus bars. Its sole function is to stand always in readiness to take the excitation of the alternators in case the exciters should fail, and thereby prevent the shut down of the entire station. Such batteries are usually small and comparatively inexpensive, and since they are kept fully charged and are but little used, their maintenance cost is very low and life almost indefinitely long.

Usually they "float" across the bus bars, and the bus bar voltage being practically constant, there is no current flow either into or from the battery. Under this condition a large number of the cells are end cells, and an end cell switch is used, which has a correspondingly large number of points. The object of the large number of end cells is to enable discharge to continue down to 1.55 or 1.6 volts per cell if the battery must deliver current for an excessive length of time as compared with its normal rating.

Installations have been made in which boosters are used instead of end cell switches, as will be later described.

The size of battery adopted depends on the conditions. In some cases the battery is large enough to supply the total exciting current for the station for half an hour, while in other cases the capacity is large enough to furnish this current for two hours. A battery which will supply the exciting current for an hour when the load is heaviest should be amply large. The time of current supply from the battery is only that required to get the exciter back into operation, and unless an injury has been done that is so serious as to make repairs a matter of several hours delay, it usually will

require only a few minutes to locate the trouble and put the exciters to work again.

Where the number of cells is large, it is necessary to arrange some means for keeping them fully charged. One method is that described in Chapter XLII, where the battery is divided into two parallel groups for charging. Another arrangement is that of an ordinary charging booster which is used about twice each month to bring the battery up to full charge. The booster may be in series with the battery, or it may simply be connected across the end cell switches as shown in Fig. 271. In this latter case the booster charges only the end cells, and the main battery is charged by the exciters.

If the exciter bus bar voltage be 125 volts and the cells are to

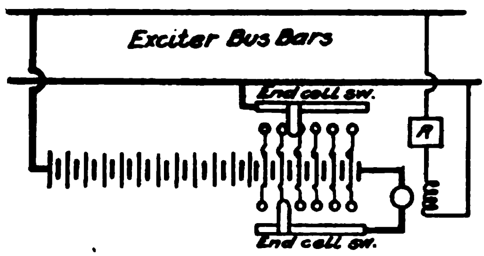


FIG. 271. Connections for Exciter Battery with Booster.

discharge down to 1.6 volts per cell, the number of cells $= \frac{125}{1.6} =$ 78 cells.

Maximum charging voltage $= 78 \times 2.6 = 203$ volts.

Maximum booster volts $= 203 - 125 = 78$ volts.

No. of cells floating across bus bars $= \frac{125}{2.05} = 61$.

No. of end cells $= 78 - 61 = 17$.

End cell switch points $= 18$.

If booster is connected across end cells, the main battery cells must be brought up to 2.6 volts per cell by the bus bar pressure. Therefore the end cell switch must have a sufficient number of points to cut out all but $\frac{125}{2.6} = 48$ cells, in which case the number of end cells $= 78 - 48 = 30$ and the number of end cell switch points $= 31$. Obviously the simpler and less costly equipment is to connect the booster in series with the bus bars for charging.

All the foregoing applies to exciter systems in which the exciter bus bar voltage is fixed and constant. The arrangements described are not practicable in stations where exciter voltage regulators are used which automatically change the exciter voltage to correspond with load changes on the alternators.

In the case of current fluctuations, a storage battery tends to maintain a constant load on the generator, but when the generator voltage fluctuates, a storage battery multiplies variations in load, or, if none exist normally, will produce them, so that, far from being a power regulator, it becomes an additional varying load. The reason of this is obvious after a consideration of the conditions. An increase in voltage with a given load across the bus bars means an increase in energy output proportional to the square of the voltage increase; while a diminution of voltage means a reduction in energy likewise proportional to the square of the voltage decrease. Also, when the voltage increase takes place, a current flows to charge the battery, which flow is proportional to the voltage increase, the energy to the battery being proportional to the square of the increase in bus bar pressure. When the voltage is diminished the battery delivers current to the bus bars, thus decreasing the generator load by an amount proportional to the square of the diminution in voltage, and at the same time that the bus bar load has decreased. Therefore a floating battery on a variable voltage system, in which the external load varies with the impressed voltage, augments the load fluctuations.

For this reason, special regulating means must be adopted for exciter batteries connected to voltage-regulated bus bars. One method is to put a series booster in circuit with the battery, the field winding being connected to produce an electro-motive force in a direction to oppose current flow through it. If the bus bar voltage is higher than that of the battery and tends to send current, through the booster, into it, the current flow through the shunt coil will produce a booster voltage to oppose this flow, and if the battery voltage is the greater, and tends to discharge to the bus bars, the series coil will set up an opposing voltage to prevent this discharge. Obviously some current flow must take place to produce the required booster voltage, and in order to keep this current within small limits it is necessary to use a comparatively large size booster with many series turns. Another method is to use a booster with a few series turns which act as a pilot field and a shunt

winding connected across the booster brushes. When current flow takes place through the series winding and a slight opposing booster voltage is produced, the shunt coil will also set up a pressure in the same direction as the series winding, and the effect being cumulative, the shunt coil will build up the booster voltage until current flow in the series coil is zero, or possibly until it is reversed and causes the shunt field to disappear.

Woodbridge has produced a special form of externally controlled

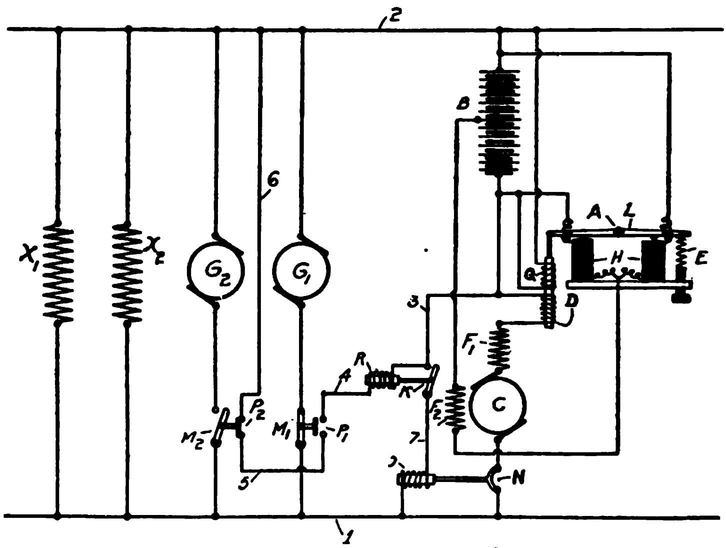


Fig. 272. Woodbridge System for Exciter Batteries.

booster system for this service.* The connections are shown diagrammatically in Fig. 272.

1—2 represent the main conductors or bus bars of an exciter circuit to which current is supplied by the generators G_1 and G_2, for exciting the field coils X_1 and X_2, the voltage across the bus bars 1—2 being varied automatically by a voltage regulator. A storage battery B with a booster C in series therewith is connected across the bus bars 1—2. The booster C is provided with a series coil F_1 which is so connected as to produce a voltage in the booster C opposing the flow of current therethrough. A second coil F_2 is also provided, the current in which is controlled by the carbon regulator A. This regulator is fully described in

* Amer. Pat. No. 941601

Chapter XXXV, and consists of two piles of carbon disks H, upon which a lever L bears in such a manner that pressure on one end of the lever will increase the pressure on one of the piles and decrease that on the other.

The pressure at one end of the lever is produced by a solenoid D connected in the battery circuit, the pull of this solenoid being balanced by an adjustable spring E at the other end. A polarizing coil Q is also shown connected across the battery terminals, which serves to polarize the core of the solenoid. Thus any flow of current through the coil D in one direction will pull down on the lever, while a flow in the other direction will relieve this pull. The two piles of carbon disks are connected in series across the battery terminals, while the field coil F_2 is connected between the intermediate point in the circuit between the two carbon piles and the middle point of the battery. A flow of current from the battery through the coil D in the discharge direction, caused for example by a drop in the voltage across 1—2, will so change the relative pressures on the two carbon piles H H and therefore their relative resistances as to cause a flow of current through the coil F_2 which will produce a voltage in the booster C to oppose the discharge current from the battery. By properly proportioning the parts of this apparatus a very small charge or discharge current in the battery circuit may be made to produce a voltage in the booster C sufficient to compensate for wide fluctuations of voltage on the circuit 1—2.

Connected around the booster C is shown a circuit 3—7 containing the switch K and a solenoid O. When the switch K is closed this circuit serves to connect conductor 1 directly to the corresponding terminal of the battery, thereby short-circuiting the booster C and permitting the battery to discharge directly into the exciter circuit. The switch K is closed by a solenoid R which is connected into a circuit leading from one terminal of the battery by way of conductors 3, 4, 5, 6, and 2 to the other terminal of the battery. There are two interruptions in this circuit at P_1 and P_2, which may be closed by contacts mechanically connected to the corresponding generator switches M_1 and M_2 and are thus closed when these generator switches are open. The circuit 4—5—6 is therefore completely closed only when both generator switches M_1 and M_2 are open. So long as either generator G_1 or G_2 is supplying the current to the circuit there will be no current

in the solenoid R and the switch K will remain open. If, however, both switches M_1 and M_2 are open so that the normal supply of current from the generators G_1 and G_2 to the exciter circuit is entirely interrupted, current will flow through the solenoid R, closing the switch K and connecting the battery directly across the bus bars 1—2, permitting it to furnish the current supplied from those bus bars. By closing the switch K a short circuit is established around the booster. This latter is protected from an excessive flow of current under these conditions in two different ways. First, the effect of a flow of current in the field coils F_1 and F_2 (the latter being produced by current in the solenoid D) will produce a booster voltage tending to oppose this flow of current and limit it to a negligible amount. Second, the flow of current in the solenoid O will open the switch N and disconnect the booster.

CHAPTER XLVI.

ALTERNATING-CURRENT SYSTEMS.

SINCE the storage battery is operative only on continuous current, it can be used only in connection with alternating-current systems by the interposition of some current-rectifying means.

There are three devices for rectifying the alternating current, viz., the mercury vapor rectifier, the motor generator, and the rotary converter.

The mercury vapor rectifier is not reversible, *i.e.*, it cannot change direct into alternating current, and therefore it can only be used for charging batteries or delivering current to circuits which have their load changes regulated by batteries.

The motor generator and the rotary converter are reversible, and, in connection with a battery, with proper auxiliary apparatus or particular methods of construction later to be outlined, may be made to regulate a fluctuating alternating current. A battery then may be made to

(1) Receive charge from an alternating-current circuit.

(2) Regulate the load on a direct-current circuit fed from an alternating-current circuit.

(3) Furnish storage for a direct-current system fed from an alternating-current circuit.

(4) Regulate the load on an alternating-current circuit.

(5) Furnish storage for an alternating-current circuit.

(6) Regulate the load on both an alternating-current circuit and a direct-current system fed from the alternating-current circuit.

(7) Furnish storage for both an alternating-current circuit and a direct-current system fed from the alternating-current circuit.

The first three cases present no problems that have not been discussed in previous portions of this work. The battery simply regulates a direct-current load delivered at constant potential, and it makes no difference whether the source is a direct-current generator or rotary converter. It is only necessary to put in a booster with its driving motor and a regulator in the direct-current side of

the system between the source of power and the load, just as has been set forth in preceding chapters. The regulation of alternating-current or mixed systems presents more difficult conditions and these are discussed in subsequent chapters.

Figs. 273 to 278 inclusive represent the principal methods of regulating alternating and mixed systems by storage batteries and proper apparatus. In each of the figures A is the source of alternating current, B a booster, C a controller responsive to fluctuations

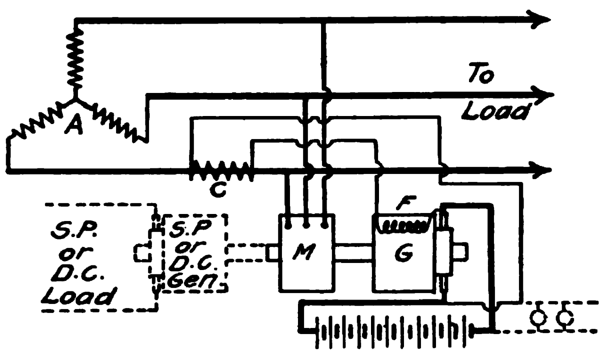


FIG. 273. Motor-Generator Regulating System.

in the alternating-current circuit and working to regulate the field F, M is a motor, G a generator, R a rotary converter.

The figures are all diagrammatic, and no switches, meters or other devices are shown. Fig. 273 shows a direct-current generator driven by an alternating-current motor, a battery being connected across the brushes of the generator. The generator field F is varied by controller C responsively to changes in the alternating-current load, so that the field excitation is diminished with increase in load. This allows the generator voltage to fall below that of the battery, which latter discharges into the generator, causing it to become a motor driving the alternating-current motor M as a generator and thus feeding the alternating-current circuit. When the load is normal neither motor nor generator does any work, and the voltage of G is equal to that of the battery.

By proportioning M and G to take additional load, a generator on the same shaft will be driven and another form of power may be supplied, either single-phase, alternating-current, constant potential, direct-current or multiphase, alternating current of a frequency

different from that of the main system. Such an additional generator is indicated in dotted lines. Obviously any load change on this third machine will be equalized, because such change will cause a variation in the energy delivered by the alternating-current system to the driving motor, and this will produce a change in the field excitation of G such that the battery will discharge on increase in load on the third machine, causing G to assist M in rotating the shaft.

Also, direct current may be taken from the brushes of G, but its voltage will fluctuate between the maximum and minimum values of battery voltage.

Fig. 274 shows an arrangement similar to that shown in Fig. 273 but with a booster in the line between the battery and the genera-

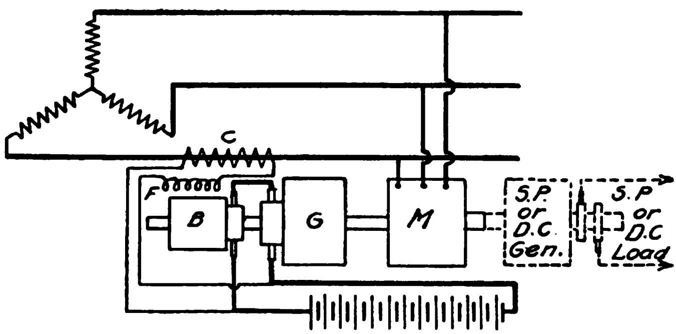


FIG. 274. Motor-Generator and Booster Regulating System.

tor brushes. The booster in this case is mounted on the same shaft as M and G and is driven by whichever of these machines is acting as a motor, by M on charge and G on discharge. As in the first case, a third generator may be mounted on the shaft provided M and G are proportioned to drive it, and also take care of the energy that must be provided for on charge or discharge.

Direct current may be taken from the brushes of G, which is slightly variable, the variation being that due to the current through G multiplied by the resistance of its armature.

Fig. 275 shows a rotary converter with an alternating-current booster on the same shaft and both, of course, running synchronously. The controller C regulates the field of the booster and in this way the voltage at the rotary slip-rings is varied with varia-

tion in the alternating-current load. This varies the direct-current voltage and causes the rotary to change from a "direct" to an "inverted" condition, receiving alternating current and converting it into direct current, which passes to the battery when the

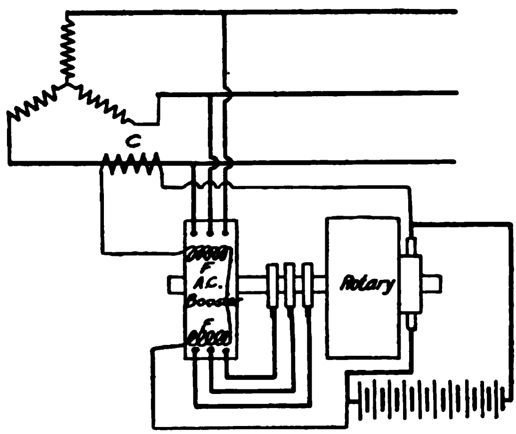


FIG. 275. Rotary Converter Regulating System.

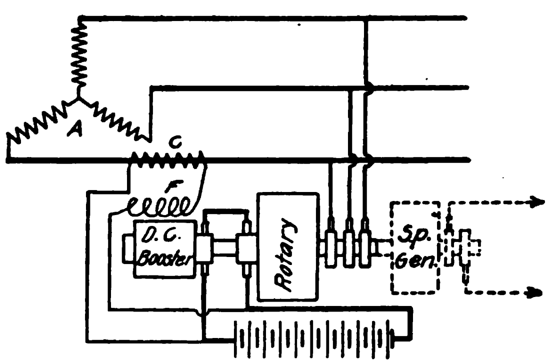


FIG. 276. Rotary Converter Regulating System.

booster voltage is in one direction, or receiving direct current from the battery and transforming it to alternating current which is fed to the alternating-current lines.

Although the booster is an alternating-current machine, it, being mounted on the same shaft with the rotary, may have a voltage to assist or oppose the flow of alternating current from the line to the

rotary depending on the field excitation, and in this sense may be considered as directional.

Just as in the case of the previously described mixed systems, an additional generator may be mounted on the shaft to deliver cur-

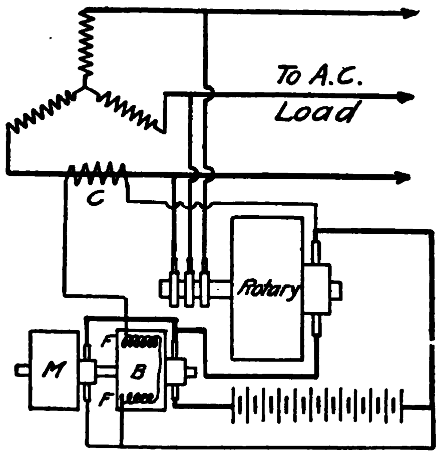


FIG. 277. Rotary Converter Regulating System.

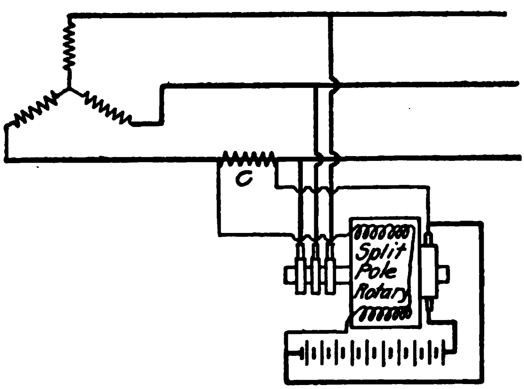


FIG. 278. Split Pole Rotary Converter Regulating System.

rent to a second circuit. Also, direct current may be taken from the direct-current brushes of the rotary, but its voltage will fluctuate with that of the battery.

Fig. 276 shows a rotary converter with a direct-current booster mounted on its shaft. The conditions of operation are all just as indicated in the description of Fig. 275, except that direct current

having a voltage that fluctuates only slightly — i.e., by the amount Ir, in which r is the resistance of the rotary armature — may be taken from the direct-current brushes.

Fig. 277 shows the same arrangement, electrically, as depicted in Fig. 276, the difference being that the booster is driven by its own direct-current motor. The motor may be an alternating-current machine if desired.

Fig. 278 shows the connection for a split-pole rotary converter which is for regulating an alternating-current system. As shown, the controller C regulates the field of the converter to change the ratio of alternating to direct-current voltage, and the same results are attained with this single machine as with a standard rotary, having a booster in circuit with it.

There may be many variants of these several methods of regulating alternating and mixed systems, and each problem is best met by some specific arrangement. Among the foregoing, however, will be found the system for nearly any possible condition of service. The descriptions of the apparatus employed, analyses of the systems described and methods of computation are given in succeeding chapters.

CHAPTER XLVII.

ALTERNATING CURRENT CONTROLLED FIELD REGULATORS.

Any of the automatic field regulators described in Chapter XXXIV may be used for controlling the field of apparatus working in conjunction with a battery to regulate the output of an alternating-current system, if the actuating windings are made to respond to the fluctuations in the alternating-current circuit. This can be done in several ways.

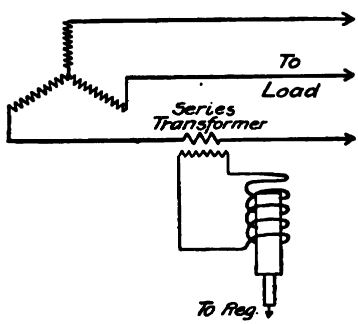


Fig. 279. Connections for Alternating Current Controlled Regulator.

If the power factor is reasonably constant and the load is balanced on the phases, a current transformer having its primary winding in series with one of the main wires and its secondary connected across the terminals of the controller magnet will give fairly good regulation and maintain a constant load on the alternating-current circuit. Fig. 279 shows this connection. The form of alternating-current circuit on which these conditions would obtain is one feeding synchronous motors or rotary converters.

If the power factor is variable, but the load balanced, a double magnet winding is necessary, one winding taking current from the secondary of a potential transformer, the other winding taking current from the secondary of a series transformer. The primary of the potential transformer is connected across one of the phases which has as one side the leg in which the series transformer is connected. Fig. 280 illustrates this form of connection.

The types of alternating-current circuits on which these conditions will obtain are those in which the preponderant load is motors — either synchronous or induction — or rotary converters.

For circuits in which there are both unbalancing of load and variation in power factor the connections necessary are shown in Fig. 281. As seen, this comprises two separate magnets working on the same stem, which transmit their combined pull to the regulator. Each magnet has two windings on it, one a pressure, the other a current winding. Connected to the alternating-current circuit to be regulated are two potential and two series transformers, the secondaries of which are connected to the respective pressure and current coils of the two magnets. This arrangement gives a total magnet pull proportional to the energy in the circuit and therefore compensates for any change in power factor.

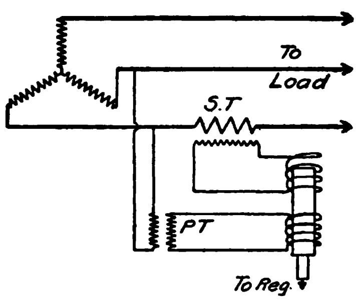


FIG. 280. Connections for Alternating Energy Controlled Regulator.

Obviously the magnets must have laminated magnetic circuits. The magnet pulls and construction of the regulators will be in nowise changed from the values and forms required for direct currents, except in the matter of the lamination of the magnet cores and magnetic circuits and the form of winding necessary.

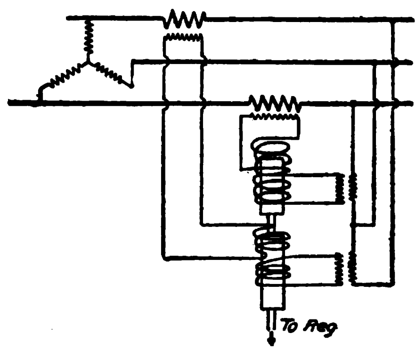


FIG. 281. Connections for Alternating Energy Controlled Regulator.

Many other possible arrangements will suggest themselves to the engineer as the need may arise. It is desirable therefore to study carefully Chapter XXXIV, in which is given a complete discussion of the principal regulators and their actions.

An ingenious form of alternating current controlled regulator is that of Woodbridge.* This device is shown in Fig. 282 and consists of an armature B provided with a bi-polar winding revolving in a four-pole field frame. This armature is connected by suitable collector rings (not shown in the drawing) to the secondary windings of three current transformers T_1, T_2, T_3, whose primaries are connected in series with the alternating-current circuit 1, 2, 3, supplied by a source, A, whose load is to be controlled. The alter-

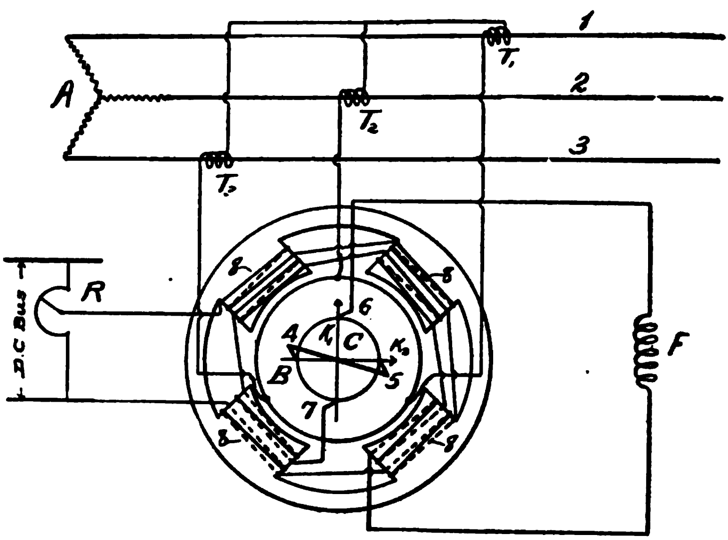


FIG. 282. Woodbridge Alternating Energy Controlled Regulator.

nating current thus transmitted through the armature winding would, if the latter were stationary, produce a revolving field proportional to the output from the source, A. The armature is, however, rotated by means of a synchronous motor in the opposite direction to that of the field rotation so as to hold this field stationary in space. There will result a stationary field whose axis is in the line of the arrow K_1. A commutator, C, is connected to the armature winding upon which bear two pairs of brushes, 4–5 and 6–7. The effect of the field K_1 would be to produce a direct-current electro-motive force between the brushes 4 and 5. A shunt winding, 8, on the four poles of this machine, controlled by the

* Amer. Pat. No. 870150.

rheostat, R, may be adjusted to neutralize the field K_1 at any predetermined output from the source, A, thus reducing the electromotive force between the brushes 4 and 5 to zero. These latter brushes are then short-circuited. If now a slight increase of load on the source A should occur, the field K_1 would no longer be neutralized by the shunt field winding and an electro-motive force would be produced between the brushes 4–5, causing a considerable current flow between these brushes. This current produces a secondary field K_2 at right angles to the first and of appreciable magnitude; and this second field produces an electro-motive force across the other pair of brushes 6–7, which are connected to the regulating field, F of the booster. In series between the brush 7 and the corresponding terminal of the field F, is connected a series winding on the poles of the exciter, designed to neutralize the magneto-motive force of the current through the armature winding between the brushes 6 and 7, so that the output from these brushes will have no disturbing effect on the exciter field.

This type of exciter possesses certain peculiar features in connection with alternating-current regulation, which may be briefly enumerated as follows:

It acts as a multiplying device by reason of the magnifying effect of the current between the short-circuited brushes, and can therefore be made exceedingly sensitive to small changes in the alternating-current load.

It can be made to respond to any desired phase component of the alternating current by a suitable angular relation between the exciter armature and the armature of the synchronous motor which drives it. Thus for controlling the charge and discharge of a storage battery this exciter would be adjusted to respond to the energy component of the alternating current.

For controlling the power factor on the alternating-current circuit the two pairs of brushes 4–5 and 6–7 may be interchanged so that the latter are short-circuited while the former are connected to a field winding on any synchronous apparatus connected to the alternating-current circuit. The exciter will then be responsive to the wattless component of the alternating current and can be made to control the field of the synchronous apparatus in such a way that this apparatus will supply practically all or any desired proportion of this wattless current. For controlling both the energy fluctuations and the power factor two such exciters may be operated,

one of which is responsive to the energy component and the other to the wattless component of current.

Another feature of this exciter is, that the secondaries of the current transformers may be short-circuited at any time, with the result of merely killing the regulating function. It is not necessary to disconnect the connections to the collector rings before doing this, even with considerable excitation in the shunt field winding of the exciter, since the armature reaction is so great that a short circuit will produce only a nominal flow of current sufficient to demagnetize the fields. Similarly, in putting the apparatus into service the rheostat, R, if properly calibrated may be set for any desired constant load on the source, A, and after all the main connections are

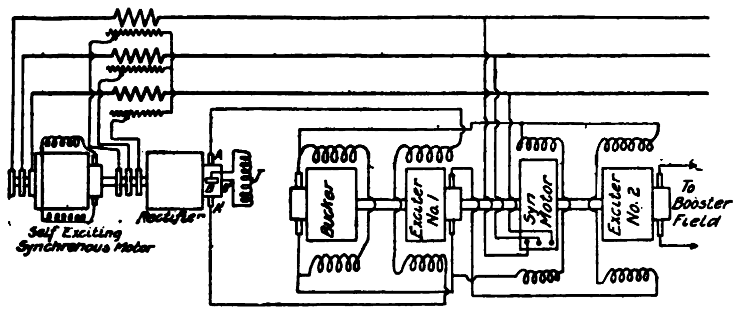


FIG. 283. Hubbard's Alternating Energy Controlled Regulator and Exciter.

closed so that the battery is merely floating on the system, the short-circuiting switch across the secondaries of the current transformers may be opened and the load on the source, A, will immediately be held at the constant predetermined value for which the rheostat, R, has been set.

Another regulating device for alternating currents is that of Hubbard.* This is devised to regulate the load in accordance with the variations in energy, and compensates for power factor.

A diagram of the arrangement is shown in Fig. 283. It comprises six dynamo-electric machines, exclusive of the booster. They are, however, all very small, and for that reason not so costly as might at first appear.

The machines all have their titles given in the figure.

Current is taken from the secondaries of the three, star-connected, series transformers and led to the slip-rings of a rectifier

* Am. Pats. Nos. 869244 and 869279.

armature which is mounted on the same shaft as a self-exciting synchronous motor. This motor receives current from the alternating-current circuit, as shown, and its speed synchronizes with the voltage waves of the system.

The rectifier consists of an armature having a bipolar winding with the slip-rings connected at 120-degree spacings, for a 3-phase system. For single-phase systems, there are but two slip rings, and only one series transformer is required. At the opposite end of the armature is a commutator having two pairs of brushes A, A^1 and B, B^1. Three-phase current in the rectifier will produce a rotating magnetic field. The synchronous motor rotates the rectifier armature in a direction opposite to that in which the rotating magnetic field travels. As the synchronous motor armature turns in synchronism with the voltage of the system, and the rotary field of the rectifier is in synchronism with the current, there is produced, in space, a field whose position is stationary so long as the power factor remains unchanged. A change in current without a change in power factor merely increases the magnitude of the field, but does not change its position.

The pair of brushes, A, A^1, arranged diametrically opposite, and bearing on the commutator at points of maximum voltage when the power generated is at 100 per cent power factor, will give a direct current which will vary in accordance with variations of the alternating current transmitted, independent of change of power factor within very wide limits, because the current transformers feeding the rectifier tend to preserve their current transformation ratio irrespective of changes in resistance of their secondary circuits. When the position of the field changes, the voltage on the commutator of the rectifier also changes, and rises until of sufficient value to deliver a direct current over the circuit connecting the A brushes equal to the transformation ratio value of the current transformers. A second set of brushes, B, is used on the commutator at 90 electrical degrees from the A brushes and connected to an artificial circuit J, having resistance and inductance characteristics properly related to the characteristics of the circuit connected to the A brushes, forming a by-pass, and two direct currents are obtained, one of which, a′, varies as the energy current component and the other, b′, as the wattless current component of the current in the alternating-current line. a′ is used to regulate the battery charge and discharge, and b′ can be used

to correct the power factor by changing the excitation of a synchronous motor or a synchronous converter. The direction of b′ is in one direction for lead and in the other direction for lag.

Safety devices are provided so that in the event of trouble to the line or apparatus, the series transformers are automatically short-circuited and the regulation ceases.

From the A brushes of the rectifier, current is taken to the field winding of exciter No. 1. This latter machine is one of four mounted on a common shaft, of which one is a synchronous motor which drives the other three machines at a constant speed.

Exciter No. 1 therefore has a variable voltage, its value at any instant being proportional to the power factor and the current flow in the alternating-current mains. The field of the synchronous motor is excited from the brushes of another machine on the shaft, which, being shunt wound and run at a constant speed, gives a constant voltage. From the brushes of exciter No. 1 the current is carried to the field windings of exciter No. 2, but the constant-potential "bucker" is in series with the field circuit of exciter No. 2. The voltage of the bucker is just equal and opposite to that of exciter No. 1 when the load on the alternating-current system is equal to the average or normal load. There is no current flow, therefore, through the field of exciter No. 2. Any increase in the alternating-current load will produce a corresponding increase in the voltage of exciter No. 1. The counter pressure of the bucker will be overcome by the increased voltage, and current will flow in the field windings of exciter No. 2, producing a voltage proportional to the increase in alternating-current load. If the load on the alternating-current system is reduced, the voltage of exciter No. 1 is correspondingly reduced. The voltage of the bucker will overcome the diminished voltage of exciter No. 1, and as a result the field of exciter No. 2 will be energized in the direction opposite to that in which it is excited when the "bucker" voltage is lower than that of exciter No. 1.

The voltage of exciter No. 2 will therefore vary from zero to positive maximum and to negative maximum, according to the change in the load on the alternating-current circuit.

The current from exciter No. 2 goes to the field of the booster (not shown) and the booster voltage changes, therefore, with the load it is to regulate, through the intermediary of motor generators or rotary converters.

If the booster were a 200-K.W. machine, with either compensated or inter-pole windings, the exciting energy would be 0.5 per cent, or 1000 watts, which would be the maximum output of exciter No. 2. If this momentary maximum be considered as a 100 per cent overload, the actual size of the exciter No. 2 will be 500 watts.

If exciter No. 2 requires 6 per cent of its output for excitation, the energy for its fields will be 30 watts. The change in voltage of the rectifier, and consequently the change in the excitation of exciter No. 1, does not vary in proportion to the change in the alternating-current load, but varies only slightly, above or below the voltage produced by normal load. The change in rectifier voltage is about 15 per cent of the normal for maximum or minimum alternating-current load. Assuming that the load on the alternating-current system is maximum the voltage of exciter No. 1 at maximum load will be 1.15 times the normal. If the normal voltage of exciter No. 1 is 50 volts, that of the bucker is also 50 volts, at maximum load the voltage of exciter No. 1 will be $50 \times 1.15 = 57.5$ volts and it will deliver $57.5 - 50 = 7.5$ volts net to the field of exciter No. 2. To give 30 watts at 7.5 volts requires 4 amperes, so that the output of exciter No. 1 is $4 \times 57.5 = 230$ watts.

The size of the bucker must be such as to give 50 volts and a continuous-current output sufficient to excite the field of the synchronous motor, with a second current fluctuating above and below the continuous normal current.

When exciter No. 1 has a voltage greater than that of the bucker, the current in the bucker armature is equal to the field current of the synchronous motor minus the current to the field of exciter No. 2. If the motor has a rating of 750 watts, and requires 6 per cent for field excitation, this is 45 watts, or $\frac{45}{50} = 0.9$ ampere the bucker must furnish continuously. With 0.6 ampere from bucker to booster field, the output of the bucker is $50\ (0.9 + 4) = 245$ watts.

The rectifier is made to deliver about 45 watts, or 4.5 amperes, at 10 volts from the A brushes.

In practice the machines are made larger than this so that a much greater excitation can be given each machine than necessary and thereby overcome the time lag as explained in Chapters

XXXIII and XXXIV. The excess voltage at the booster is reduced by a differential series coil on the booster that has the action described in the discussion of Hubbard's booster, Chapter XXXIII.

Adjustment of normal load on the alternating-current system is effected by shifting the variable connections to the secondaries of the series transformers. The system shown in the diagram is used only when the voltage variations on the direct-current side of the converter (or motor generator set) are excessive. Generally, in plants where very close regulation is not required, the current from the rectifier goes directly to the field of the counter E.M.F. exciter, the other machines shown being omitted.

CHAPTER XLVIII.

CURRENT CONVERTER SYSTEMS.

THE devices whereby current may be changed from alternating to direct are the mercury vapor rectifier, the motor generator and the rotary converter. These will be discussed in this chapter, together with their relation to storage battery regulation and equipments.

Mercury Vapor Rectifier.

This consists of a vessel of glass or other non-conducting substance which is capable of withstanding heat and holding a vacuum, with a pool of mercury in a depression at the bottom, and suitable electrodes fastened to proper points on the inside, the air being exhausted from the vessel. Since no high vacuum — that is, of the order of one ten-millionth of an atmosphere — can be produced or maintained in any vessel except such as are made of vitreous substances, glass is universally employed.

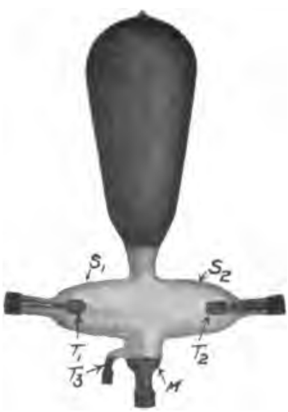


FIG. 285. Mercury Vapor Rectifier.

One of the several forms is shown in Fig. 285. The rectifier shown is for the conversion of single-phase alternating current, and at present (1910) no multiphase rectifiers are on the market, though they have been made and successfully operated. They are also available only in small sizes, that is, up to 50 amperes capacity. As their characteristics of low cost, high efficiency and no need of attendance make them suitable for many conditions where rotating machines are now used, it is inevitable that they will come into use for service of considerable magnitude, though this time may be deferred until some time subsequent to the expiration of the basic patents.

Referring to Fig. 285, M is a pool of mercury in the bottom of the

bulb forming one electrode, and it is the one to which the current continuously flows, that is, it is the cathode. Therefore the wire connected to it is always the positive side of the direct-current mains.

T_1 and T_2 are terminals of carbon, flattened, hollowed out or otherwise shaped to give a large surface. These are supported inside the branch arms S_1 and S_2. These terminals are arranged with reference to making the distance from T_1 or T_2 to M reasonably small, and yet to preserve such a distance between T_1 and T_2, or otherwise shield them, that there will be no danger of a short circuit forming between them. To prevent this the old types of Westinghouse rectifiers depended on the shielding action of glass tubes in which the electrodes were placed. They surrounded the terminals, but were provided with openings cut in the tubes to allow passage of the current, these openings being made on the side of each tube furthest away from the other one. By this arrangement the path from T_1 to T_2 was made of considerable length, without removing them a great distance away from M.

The design shown in Fig. 285 is that now used by both the General Electric and Westinghouse Companies. In this the electrodes T_1 and T_2 are held in tubes that extend out from the main chamber, with the mercury electrode placed halfway between them, thus giving a greater distance between carbon electrodes than from either carbon electrode to the mercury. T_3 is an auxiliary mercury electrode for starting the action of the rectifier, as will later be explained.

The action of the rectifier is based on the peculiar property of a mercury electrode of setting up an enormously high resistance to the passage of current in one direction after current flow in the opposite direction has once been established. In this way it acts as an electrical check valve, permitting current to flow in one direction only.

There are several theories of the cause of this phenomenon, but the high resistance of the mercury cathode to the outflow of any current unless some means are used to start current flow from it, seems the rational one.

The mercury cathode also opposes the flow of current into it until, by some means, the flow is started against this opposing resistance, after which it offers but little opposition to the passage of current, as long as the flow to it continues. If at any instant

the flow ceases, the high cathode resistance is immediately set up and the rectifier becomes inoperative until started again.

When in operation, the heat produced by the current entering the mercury cathode vaporizes some of the mercury, and the hot vapor rises up in the vessel, and impinging on the walls is condensed, and falls back again to the pool below. The vessel therefore has two functions, one as a receptacle for the electrodes and to maintain a vacuum about them so that the current flow is unimpeded, the other is to act as a condensing chamber and present a surface, cooled by the atmosphere, against which the hot vapors may impinge and be condensed. This latter function is the factor that fixes the size of the vessel, the area exposed being proportional to the watts loss in the rectifier. In the present designs, the watts radiated per square inch range from 0.35 to 0.6 watt, the higher value being for blackened condensing chambers. The watts lost are directly proportional to the current flow, owing to the fact that the resistance drop is constant and practically independent of either the current or applied electromotive force. The drop across the terminals varies in different designs from 15 to 22 volts. Obviously the efficiency varies directly with the voltage of the circuits on which the rectifier works. For a 20-volt drop and 40 volts applied pressure, the efficiency will be only 50 per cent, while for 1000 volts pressure the efficiency will be $\frac{1000 - 20}{1000} = 98\%$.

There is a minimum current below which the cathode resistance becomes unstable and the rectifier will not operate. This current is about 5 amperes.

There are two general methods of starting the converter. One is to impress a high voltage between the mercury cathode and an auxiliary starting terminal and break down the cathode resistance; the other is to use an auxiliary starting mercury electrode and tilt the vessel until the mercury of the main and the auxiliary electrodes is in contact and current flows through the circuit thus made from any suitable source. On returning the vessel to its normal vertical position, the two bodies of mercury separate, and the arc drawn between the two, breaks down the cathode resistance and allows the in flow of current from the carbon electrodes. The auxiliary mercury electrodes T_3 shown in Figs. 285 and 286 depict this latter arrangement.

The pressure necessary to start the rectifier where high poten-

tials are used with starting terminals, ranges from 10 to 15 thousand volts, so that a special transformer or induction coil is a necessary part of the equipment. It has however been found that a starting ring of metal placed around the outside of the cup-shaped portion of the vessel containing the mercury will start the operation of the rectifier if a pressure of 5 or 6 thousand volts be impressed across the band and the terminal leading to the mercury pool. This is due to the high specific inductive capacity of the glass.

The electrical connections of a single-phase converter are shown in Fig. 286. As indicated, a special transformer having a middle tap is required, the lead from this tap forming one side of the direct-current line.

The operation is as follows:

The tube is tilted to the left and the mercury pools in M and T_3 join, making a circuit from the positive side of the battery through coil 1, the starting resistance, and the left half of the transformer winding. On returning the bulb to its vertical position the two bodies of mercury separate, an arc being drawn between them. The current then begins to pass from one of the electrodes to M and deliver direct current to the battery. Since a single-phase circuit has four periods in every cycle in which the current is zero, the rectifier would cease operation instantly unless some preventive means were used to obviate this. The ballast reactances J_1 and J_2 are used to maintain the current flow over the periods when it would normally be equal to zero. The curves shown in Fig. 287 explain this action.

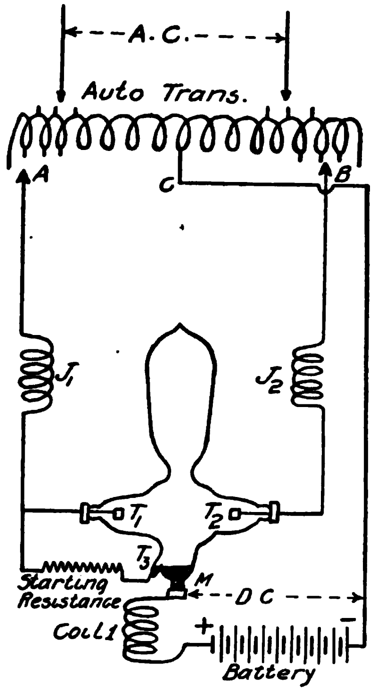


Fig. 286. Connections of Mercury Vapor Rectifier.

Curve 1 is the curve of alternating voltage delivered by the incoming circuit.

Curve 2 is the curve of alternating voltage in the transformer winding (the secondary in the case of a voltage-changing transformer) from B to C.

Curve 3 is the voltage in the transformer winding from A to C.

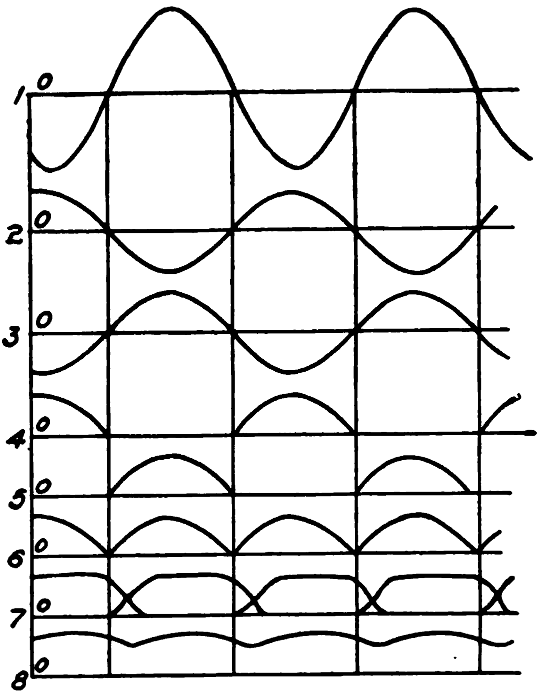


FIG. 287. Curves of Current and Voltage in Mercury Rectifier.

During the period in curve 2 when the voltage is positive, *i.e.*, the curve lies above the zero line, current flows from B through T_2 to M, through coil 1 to the battery and up to C; while during the time when the voltage curve 3 lies above the zero line, current flows from A through T_1, to M, through the battery and back to C.

Curve 4 shows the current impulses from B through the rectifier, while curve 5 shows the current from A through it, their sum being indicated in curve 6. This latter curve shows the existence of the zero points at which the rectifier would cease operation if the reactances were not included in the alternating-current circuit.

When the impressed electromotive force from A to C falls to zero, the current through T_1 continues to flow, due to the discharge

of the inductance, J_1, and gradually dies down to zero after the electromotive force has passed its zero point and reversed in direction. This means that current flow begins from T_2 through the rectifier before the current from T_1 reaches zero. In the same way the current flow from T_2 overlaps that of T_1.

Curve 7 show the current flows from each of the two electrodes, and the overlapping produced by the reactances.

Curve 8 is the combined curve and is the direct current delivered to the circuit. This current is pulsating in character, as indicated. When the pulsations are greater than admissible, an inductance in the direct-current circuit such as coil 1 in Fig. 286, will smooth out the waves by absorbing energy when the current is at its maximum value, which it delivers to the circuit during the period of minimum flow.

In the practical devices made for battery charging, coil 1 serves as a magnet winding as well as an inductance, the magnet controlling an automatic device which draws the tilted tube to its vertical position when current flows through the coil.

Obviously, with multi-phase currents no ballast reactances are necessary, as the current flow from one electrode does not cease until after that from another electrode begins.

The voltage ratio between the direct and the alternating currents is partly influenced by the design. From curve 8, Fig. 287, it is clear that the current value — which is proportional to the electromotive force — is the square root of the mean square of the curve. The amount of pulsation in the curve depends on the value of the ballast reactance and the amount of overlap of the currents from the individual electrodes. Also, the current begins to flow only when a pressure of 18 volts or more exists between the electrodes and the cathode M. To find the direct-current voltage, therefore, it is necessary to plot curves similar to those shown in Fig. 287, and, taking the curve like curve 7, give it suitable ordinates to represent voltage, and then within the curve of each electrode draw another curve with ordinates 18 volts less than the ordinates of the first curve. It must be remembered that the voltage curves taken represent the voltages measured between one side of the transformer and its middle point, and includes the effect of the ballast reactance. The transformer voltage is approximately double that of the voltage impressed between either electrode and the cathode.

In general voltage of the load plus the drop in bulb and sus-

taining coil = 45% of the effective A.C. voltage applied to electrodes A and B. Bulb drop varies with the vapor pressure in the bulb and therefore with its temperature, ranging between 20 and 25 volts when cold and about 5 volts less when hot. This is also affected by the length and shape of the current path in the bulb and therefore varies in different bulbs.

Mercury vapor tubes being of glass are fragile and must be handled with extreme care. They must not be started on full load when very cold without some preliminary warming, which may be done by starting and running a few minutes with a current of 8 to 10 amperes.

These rectifiers as made at present have a life of only 500 to 800 hours. There is no reason, however, why they should not be as permanent as any other device, as the mercury cannot oxidize or change its composition. To make a permanent rectifier requires extreme care in the preparation of the carbon electrodes and protracted exhausting of the tube. Some have been made in this way which have been under operation for 26,000 hours and still show no signs of deterioration. Possibly certain trade reasons cause the production of the short-life bulbs.

Several arrangements of complete battery-charging sets are marketed, nearly all of which are provided with automatic devices for tilting and then drawing the bulb to vertical at starting, and for opening the circuit to the rectifier when the battery is fully charged. They also have dial switches the movement of which will change the amount of reactance in circuit, the number of transformer turns between the incoming alternating-current mains and the number of transformer turns between the leads to the rectifier, so that any desired current and voltage adjustment may be made.

Motor-Generator.

This may be made up of either an induction or a synchronous motor driving a direct-current generator.

If the motor-generator is to work in connection with a battery to regulate the alternating-current load, the synchronous motor is the better one to use. An induction motor requires considerable increase in speed to change from a loaded motor to a loaded generator, and speed changes cannot be made quickly enough to give good regulation. For charging only, or for supplying a direct-current circuit on which the load fluctuations may be taken up by an ordinary battery and booster equipment, the induction motor may

be used, and owing to its simplicity and low cost is generally the preferable one. Where a synchronous motor is used, a starting box is provided for the direct-current machine, and this is used to bring the set up to speed when starting up the unit, the starting current being supplied by the battery. Proper switches cut this starting box out of circuit when the set is running from the alternating-current supply and ready to put into service. When used for charging or supplying a direct-current system having its own battery and booster, the direct-current machine has its voltage adjusted simply by a hand rheostat, as is customary with any direct-current generator. If the unit is to deliver a constant current to the direct-current system without the use of a booster, a regulator similar to one of those described in Chapter XXXIV may be put in the generator circuit to regulate its field excitation. This will produce fluctuations of voltage with battery charge and discharge, and therefore this system is suitable for power supply only.

When used for regulating an alternating-current system there are two methods of application.

(1) A regulator having its controlling coils in the alternating-current circuit or connected through a transformer with it, controls the generator field so that the voltage decreases with increase of load on the alternating-current system, allowing the battery voltage to overcome the opposing generator voltage and causing it to run as a motor. The motor thus driven as a generator supplies alternating current to the lines and carries the excess load. Conversely, decrease in the load on the alternating-current system will produce an increase in generator voltage, causing battery charge and taking current from the alternating-current lines to drive the motor. This arrangement is shown in Fig. 273. In this case, the generator voltage is normally equal to that of the battery, and current neither flows into nor out of the battery, the motor current being only that necessary to supply the no-load losses of the two machines. By making the size of the unit large enough, direct-current power load may be taken from the direct-current side, the battery serving as an equalizer of the fluctuations both on the alternating-current system and the direct-current load. This is due to the fact that any fluctuation of load on the direct-current side will tend to draw sufficient alternating current from the line to supply the driving motor with energy to drive the increased generator load. The regulator will respond to this increase in alternat-

ing-current load, reducing the generator voltage and allowing the battery to discharge. The battery must be of sufficient capacity to supply load increases that come coincidently on both the alternating- and the direct-current loads, plus the current necessary to drive the motor, as the motor energy on discharge or charge appears as a load increase on the alternating-current system.

In this chapter the following are the symbols used, with their significance.

J = energy in *watts* to the alternating-current side of the system from the battery.

J′ = energy in *watts* delivered by the alternating-current side to the battery.

E = voltage on the direct-current side.

ϵ = volts per cell of battery in series at no charge or discharge.

ϵ' = Voltage per cell on discharge.

ϵ'' = Voltage per cell on charge.

N = Number of cells, $= \frac{E}{\epsilon}$.

$E' = \epsilon' N$.

r = Resistance of armature and brushes of the direct-current circuit through generator or rotary converter.

ϕ = efficiency of motor generator or converter under the load for which computation is made.

p_1 = efficiency of booster under the load for which computation is made.

p_2 = efficiency of motor driving booster.

V = booster voltage.

F = Current to converter for transformation.

I_B = Current from battery for driving booster.

i = Current in each leg of alternating-current circuit to or from converter.

A = maximum volts drop in battery on discharge, $= N(\epsilon - \epsilon')$.

In a motor-generator system, regulating an alternating-current load only; for any output J, delivered to the alternating-current system, the generator output, when working as a motor and driving the motor as a generator will be

$$J = \frac{J}{\phi}. \tag{268}$$

Battery discharge current $I = \frac{J}{\phi E'}$ (269)

Drop through generator (as motor) armature $= rI = \frac{rJ}{\phi E'}$. (270)

Counter voltage of generator $= E' - rI = E' - \frac{rJ}{\phi E'}$. (271)

Counter voltage of generator, normal, $= E$. Percentage decrease in counter voltage is

$$\frac{E - \left(E' - \frac{rJ}{\phi E'}\right)}{E} \qquad (272)$$

In machines of large size, an exciter dynamo for controlling the field of the generator may be obviated by putting a shunt winding on the generator connected across the brushes and a second winding connected to the battery terminals through an automatic regulator. The machine and windings should be so proportioned that the shunt field winding with the minimum generator voltage across its terminals and the controller winding excited full in a direction opposite to the shunt winding will give the desired minimum generator voltage. When the controller field is excited full and in the same direction as the shunt field, the maximum generator voltage should be produced. Owing to the sensitiveness of the shunt field to variations in generator electromotive force, the controller field excitation need be only a small proportion of that of the shunt field. In the succeeding examples, the extreme possible conditions of battery discharge and maximum discharge rate, have been assumed. For normal condition of battery charge, the battery voltage, E′, will be much higher, the energy used in the auxiliaries less, and the battery current considerably lower than these examples show. Since the extreme conditions must be provided for, in view of their occasional, occurrence these computations are important, but they must not be considered as indicative of the load on the battery or machines under normal and usual conditions.

As an example take

$$J = 200 \text{ kilowatts.}$$
$$E = 500 \text{ volts.}$$
$$\epsilon = 2.1 \text{ volts.}$$
$$\epsilon' = 1.65 \text{ volts.}$$
$$N = \frac{500}{2.1} = 238.$$
$$r = 0.08 \text{ ohm.}$$
$$\phi = 92\%.$$

$$\text{Battery current} = I = \frac{200{,}000}{92 \times 1.65 \times 238} = 552 \text{ amperes.}$$

Drop through motor $= 552 \times 0.08 = 44.16$ volts.

Counter voltage $= E' -$ drop $= 392.7 - 44.16 = 348.54$ volts.

Percentage decrease in generator voltage is

$$\frac{500 - 348.5}{500} = 30.3 \text{ per cent.}$$

If the generator characteristic were a straight line, the change in the voltage across the shunt field would give the required change in field excitation, but the machine would be unstable and inoperative.

From the characteristic of the dynamo adopted, the maximum and minimum excitation necessary may be found and the proper windings computed.

All the foregoing is based on the use of synchronous motors in which there is no speed change. If induction motors are used, the speed will have to be varied to change them from motors to generators and *vice versa*, and the amount of speed change will depend on the size and design of the motors.

If the per cent slip is taken as s, then the speed when carrying maximum load will be $(1 - s)$ S, in which S is the synchronous speed.

The speed at which it must be run to give its maximum output as a generator will be $(1 + s)$ S.

Then for case 1 preceding, the current from the battery would be the same as computed, namely $\frac{J}{\phi E'}$, and the other equations would hold except equation (272), which would become

Percentage change in field excitation

$$= \frac{\left(E - \left(E' - \frac{rJ}{\phi E'}\right)\right)(1 + s)}{E}. \qquad (273)$$

That is, the change in field excitation must be $1 + s$ greater than in the case of a synchronous motor.

Case 2. To regulate an alternating-current system, the direct-current side of the motor-generator may have a booster in circuit between the generator and the battery, the booster having its voltage regulated by a controller which is connected to respond to changes in the alternating-current circuit. This arrangement is

indicated in Fig. 274. With this system, either lights or power may also be taken from the direct-current side if a reversible booster be used, or power may be taken from the direct-current side if a non-reversible booster be used. In computing the size of the booster and its range of voltage and the size of the motor-generator set the following conditions must be considered.

Let J = *watts* excess of maximum load above normal on the alternating-current system, which is the maximum amount of energy the battery must supply on discharge, and all other quantities as before given.

For a synchronous motor, the speed does not change and therefore the speed of the generator remains also constant when it works as a motor, and, with the exception of a small change in voltage due to armature reactions, the voltage of this machine may be also considered as constant.

In practice the motor, generator and booster would be mounted on the same shaft, the generator acting as motor to drive both the alternating-current motor as a generator and the booster when discharge takes place, the motor driving both generator and booster on charge.

Since neither the speed nor excitation of the generator changes, a voltage higher than that produced by the generator must be impressed on it to cause it to work as a motor supplying energy to the alternating-current lines, which increase in voltage must be furnished by the booster. If I be the current sent through the armature in opposition to the generator electromotive force, the booster must supply Ir volts for this purpose. Also the booster must, on discharge, supply a voltage equal to the drop in the battery voltage, which is $E - E'$ or $N(\epsilon - \epsilon')$. Call this quantity A.

In addition to these factors, the generator running as a motor must take enough current to supply the power necessary to drive the booster, as well as to supply the necessary energy to the alternating-current circuit. The booster voltage, on discharge, therefore is

$$V = Ir + A \tag{274}$$

and the energy output of the booster is

$$VI = I(Ir + A). \tag{275}$$

Power required to drive the booster is

$$\frac{I(Ir + A)}{p_1}. \tag{276}$$

and the energy loss in the booster is

$$\frac{I\,(Ir + A)}{p_1} - I\,(Ir + A) = jI\,(Ir + A), \tag{277}$$

$$\text{in which } j = \left(\frac{1}{p_1} - 1\right) \tag{278}$$

Total energy from the battery = IE′.

This is equal to the output of the generator (as a motor) to drive the motor (as a generator) plus the booster energy loss, all divided by the efficiency of the motor-generator, or

$$IE' = \frac{J + jI\,(Ir + A)}{\phi}. \tag{279}$$

Solving,

$$I = \frac{\phi E'}{2jr} - \frac{A}{2r} - \sqrt{\left(\frac{\phi E'}{2jr} - \frac{A}{2r}\right)^2 - \frac{J}{jr}}. \tag{280}$$

On charge, which accompanies a reduction in load on the alternating-current circuit, the energy output of the circuit to maintain the load substantially constant, is the difference between normal and minimum loads. If J′ be the alternating output to the motor this is the equivalent of ϕJ′ watts delivered to the direct-current side. The energy input to the battery is charging current multiplied by the battery voltage.

The booster must furnish an electromotive force to compensate both for the drop through the generator armature and for the increase in battery voltage above the open-circuit value. If I_c = charging current and ϵ'' = maximum voltage per cell of battery on regulation, then the energy input to the battery is $I_c\epsilon''N$.

The copper loss in the generator armature is I_c^2r. Therefore the energy actually delivered at the generator terminals is

$$\phi J' - I_c^2 r. \tag{281}$$

The booster output is VI_c in which $V = A + I_c r$ and the booster loss $= jI_c\,(A + I_c r)$. $A = N\,(\epsilon'' - \epsilon)$. Since the energy delivered by the generator is equal to the booster loss plus battery input

$$\phi J' - I_c^2 r = I_c\epsilon'' N + jI_c\,(A + I_c r). \tag{282}$$

Solving,

$$I_c = \pm\sqrt{\frac{\phi J'}{r\,(1 + j)} + \left(\frac{\epsilon'' N + jA}{2r\,(1 + j)}\right)^2} - \frac{\epsilon'' N + jA}{2r\,(1 + j)}. \tag{283}$$

The positive sign before the radical gives the only practical values of I_c.

As a practical example take an alternating-current system supplying a variable load in which

$$J = 450 \text{ K.W.} = 450{,}000 \text{ watts.}$$
$$J' = 300 \text{ K.W.} = 300{,}000 \text{ watts.}$$

Take direct-current side at 500 volts. This may be any desired voltage, but for a system of the above size should be not less than 500 volts to keep down the current and prevent the commutators, brushes, leads, switches and all current-carrying parts from being too large, cumbersome and expensive.

Take

$E = 500$ volts.

$r = 0.05$ ohm.

$\epsilon = 2.1.$

$\epsilon' = 1.65.$

$\epsilon'' = 2.3.$

$N = \dfrac{500}{2.1} = 238.$

$\phi = .82\%$ at 200% overload *exclusive* of generator copper loss.

$E' = 1.65 \times 238 = 393$ volts.

$p_1 = 0.86.$

$j = \dfrac{1}{.86} - 1 = 0.163.$

$jr = 0.163 \times 0.05 = 0.00815, \quad 2jr = 0.0163.$

$A = N(\epsilon - \epsilon') = 500 - 393 = 107$ volts.

From equation 280,

$$I = \frac{.82 \times 393}{0.0163} - \frac{107}{2 \times 0.05} - \sqrt{\left(\frac{.82 \times 393}{0.0163} - \frac{107}{0.1}\right)^2 - \frac{450{,}000}{0.00815}}.$$

$= 1540$ amperes, which is the maximum battery discharge

Booster output $= 1540\,(107 + 0.05 \times 1540) = 281.8$ K.W.

Booster loss $= .163 \times 281.8 = 45.9$ K.W.

Total generator (as motor) output $= 450 + 45.9 = 495.9$ K.W

Total generator input $= \dfrac{495.9}{.82} = 604.75$ K.W.

Battery output $= 1540 \times 393 = 605$ K.W., which checks witl the generator input required, within the limits where large quan tities enter into the computations and decimals are suppressed.

On charge

$$J' = 300 \text{ K.W.}$$
$$\phi J' = .82 \times 300 = 246 \text{ K.W.}$$

From equation 283,

$$I_c = \sqrt{\frac{246{,}000}{0.05815} + \left(\frac{547.4 + 7.73}{0.1163}\right)^2} - \frac{555.13}{0.1163} = 424 \text{ amperes.}$$

Copper loss in generator = $(424)^2 \times 0.05$ =	8.99 K.W.
Booster loss = $(47.4 + 424 \times 0.05)\ 424 \times 0.163$ =	4.74 "
Energy to battery = 424×547.4 =	232.10 "
Total energy delivered by generator =	245.83 "

which checks with the assumed energy of 246 K.W.

The maximum outputs of motor, generator and booster occur when the battery discharges, feeding the alternating-current system. The motor, acting as an alternating-current generator, delivers 450 K.W. to the lines. On fluctuating loads this maximum is momentary only, and may be taken as double the normal capacity of the motor, which, on this basis, would be a 225-K.W. machine.

If its efficiency on overload is 80 per cent, when working as a motor it must deliver, on charge, $300 \times .80 = 240$ K.W. to the shaft on which the booster and generator are mounted. This is an overload of only 15 K.W., which is negligible. This machine might be made somewhat smaller, but owing to the reactance drop through it, it would not be advisable to reduce the size below 50 per cent of the maximum output.

The maximum generator load is when working as a motor and receiving 605 K.W. If it is a compensated or inter-pole machine, 25 per cent of this amount will be a sufficient normal capacity. This will be 151 K.W.

The booster voltage to charge the battery is less than the voltage required on regulation in this particular case. Maximum booster output is on discharge and equals 282 K.W. as found on page 565. 25 per cent of this output is 70.5, say 75 K.W., which is the capacity rating of the booster.

Case 3. If an induction motor be used instead of a synchronous machine, the conditions and equations will be considerably changed.

On discharge, the booster voltage must exceed that computed in case 2 preceding, by a percentage equal to the slip s, because not only the battery drop and armature resistance must be overcome but the generator (as motor) must have an additional voltage impressed on it to cause it to run at a higher speed. This additional

voltage must be equal to the voltage that would exist if no speed change took place, increased by the percentage slip.

Booster voltage for no speed change = $A + Ir$.

Booster voltage for increase in speed = $(E + Ir)\,s$. (284)

Total booster voltage = $A + Ir + (E + Ir)\,s$. (285)

Substituting this value in equation 279

$$IE' = \frac{J + jI\,(Ir + A + sE + sIr)}{\phi} \qquad (286)$$

and

$$I = \frac{\phi E' - j\,(A + sE)}{2\,rj\,(1 + s)} - \sqrt{\left(\frac{\phi E' - j\,(A + sE)}{2\,rj\,(1 + s)}\right)^2 - \frac{J}{rj\,(1 + s)}}. \qquad (287)$$

If the values used in the example before given be substituted in this equation, and $s = 4$ per cent, it will be found that $I = 1561$ amperes as against 1540 amperes for the identical service with a synchronous motor. If a series coil were put on the generator, the direction of the winding being such that the voltage is increased when the generator delivers current to the battery and decreased when it runs as a motor, taking current from the battery, the work of the booster will be considerably decreased, the battery discharge lowered and the efficiency improved. These series turns should be made such that

$$I\,(r + r_1 + R) = ITk \quad \text{and} \quad T = \frac{r + r_1 + R}{k}, \qquad (288)$$

in which T is the number of turns, k the volts per ampere-turn, I the discharge current, r the resistance of the generator armature, r_1 the resistance of the series winding, and R the internal virtual resistance of the battery for normal condition of charge. Obviously the series turns cannot be proportioned for the condition of minimum battery voltage corresponding to a maximum value of R, as it would give too great a magnetization for the normal and usual conditions.

Standard Rotary Converter.

These machines are reversible and may either receive alternating and deliver direct current or *vice versa*. When receiving direct and delivering alternating current, they are said to run "inverted" and without some special damping device to absorb oscillations are liable to "hunt" when run in parallel with other machines.

The ratio between the direct and alternating current voltages is rigidly fixed and cannot be changed except in the special case of the "split-pole" rotary later to be described. If there is considerable

inductance in the alternating-current circuit leading to the rotary, the direct-current voltage may be changed within a few per cent, by varying its field excitation, but compared with the wide range of voltage variation required in storage-battery work this possible change is negligible. There are three ways in which a rotary converter may be caused to make a battery regulate an alternating-current load. One consists in putting in series with the rotary an alternating-current dynamo running in synchronism with the line and the rotary as indicated in Fig. 275. The field of this dynamo may be varied, and its voltage will vary correspondingly. This means that the alternating-current voltage to the rotary is changed, which will also change the direct-current voltage. The alternating-current dynamo is in reality a booster. Since it runs in synchronism with the system, it may have a positive or negative excitation with respect to the rotary, if it be driven by a synchronous machine. In practice it is mounted on the same shaft as the rotary, the latter machine acting not only as a converter of current but both as a synchronous motor and as a direct-current motor according to the direction of current flow through it.

A second method is to use a direct-current booster on the same shaft as the rotary, driving it by the rotary acting partly as a motor, as indicated in Fig. 276.

A third method is to use a direct-current booster driven by its own separate motor, either alternating or direct current. This arrangement is shown in Fig. 277. It is better to use a direct-current than an alternating-current motor, because on discharge, the power to drive the booster will appear as an increase in load in the alternating-current system if the alternating-current motor be used, and this energy will have to come from the battery in any case. With the alternating-current motor, this energy will have to pass through the rotary, increasing the losses and requiring a larger converter than if a direct-current motor be used.

The voltage ratios of rotary converters are as follows: Three-phase, with alternating-current at a pressure of one volt (square root of mean square value), and no current flow through it, the direct-current voltage will be, theoretically, 1.634 volts. Practically, the direct-current will be less than this ratio by an amount equal to armature drop and reactions when the rotary receives alternating and delivers direct current. The actual ratio under full load is about 1.52 volts at the direct-current brushes for each

volt impressed on the alternating-current side. When running inverted, the ratio will be about 1 volt on the alternating-current side for 1.67 volts on the direct-current side.

In a 6-phase, diametrally connected, rotary the theoretical ratio is 1 volt alternating to 1.41 volts direct, and practicaliy, 1 volt alternating gives about 1.35 volts direct. When running "inverted", the ratio is 1 to 1.43. In a 6-phase converter with the armature taps from the slip rings 60 electrical degrees apart, the voltage between adjacent alternating-current wires is 0.356 of the direct-current voltage when alternating current is being converted to direct, and when the rotary is running inverted the alternating current is about 0.352 of the direct-current voltage.

Case I. When a battery is connected in circuit with a rotary converter, the charge and discharge of which are regulated by variations of the alternating-current voltage produced by an alternating current in the booster, which under normal load has zero voltage, the quantities and equations are as follows.

The drop in voltage for direct-current flow through the armature of a rotary converter is $\mathrm{I}r$. The drop at the battery terminals due to diminished charge and maximum discharge is the same for any system of regulation, $= \mathrm{N}(\epsilon - \epsilon') = \mathrm{E} - \mathrm{E}'$. Of the energy given by the battery to the rotary converter, part will be used to drive the booster, part will be lost in heating and the remainder will appear as energy given to the alternating-current lines.

If J = energy in watts to be delivered to the alternating-current circuit, then the amperes per phase for a 3-phase system will be found from the equations

$$\mathrm{J} = iv\sqrt{3} \quad \text{and} \quad i = \frac{\mathrm{J}}{v\sqrt{3}}, \tag{290}$$

i being the amperes per phase and v the voltage between phases.

Since for a 3-phase inverted converter $v = \frac{\mathrm{E}}{1.67}$,

$$i = \frac{1.67\,\mathrm{J}}{\mathrm{E}\sqrt{3}}, \tag{291}$$

which is the current per phase through the booster.

The maximum voltage of the booster on discharge will be that due to the drop in the battery voltage plus that required to send the necessary current through the converter, and this sum divided

by the voltage ratio between the direct and alternating current sides — 1.67 in this case. The voltage of the booster measured between the slip rings is

$$V = \frac{rI + A}{1.67}, \tag{292}$$

in which A = volts drop of the battery on discharge and I = the battery current.

The battery energy output is

$$W = \frac{J + \dfrac{Vi\sqrt{3}}{p_1} - Vi\sqrt{3}}{\phi} \tag{293}$$

$$= \frac{J + \left(\dfrac{1}{p_1} - 1\right)Vi\sqrt{3}}{\phi}. \tag{294}$$

Placing $\left(\frac{1}{p_1} - 1\right) = j$, the equation becomes

$$\text{Battery energy} = \frac{J + j\,(Vi\sqrt{3})}{\phi}. \tag{295}$$

$$\text{Battery current} = I = \frac{J + j\,(Vi\sqrt{3})}{\phi E'}. \tag{296}$$

In the equations $Vi\sqrt{3}$ represents the energy delivered by the booster and $\frac{Vi\sqrt{3}}{p_1}$ is the energy delivered to the booster, their difference representing the booster loss which is supplied, together with J, by the rotary converter. Substituting in equation 292 the value for battery current found in equation 296,

$$V = \frac{r\left(\dfrac{J + jVi\sqrt{3}}{\phi E'}\right) + A}{1.67}. \tag{297}$$

Clearing and solving for V,

$$V = \frac{rJ + \phi E'A}{1.67\,\phi E' - jri\sqrt{3}}. \tag{298}$$

Case 2. Direct-current booster mounted on the shaft with the rotary converter and driven by it.

In this case the total current to the rotary passes through the booster.

Following are the equations for determining battery discharge and the size of the apparatus required.

If the output of the rotary to the alternating-current lines is J watts, the total output of the rotary as both a motor and current rectifier will be

$$J + \frac{VI}{p_1} \text{ watts,} \tag{299}$$

in which V = booster voltage and I = total current from battery.

$$\text{Input to rotary} = \frac{J + \frac{VI}{p_1}}{\phi}. \tag{300}$$

$$\text{Energy delivered by battery} = \frac{J + \frac{VI}{p_1} - VI}{\phi} = E'I, \tag{301}$$

in which $E' = \epsilon' N$

or

$$E'I = \frac{J + \left(\frac{1}{p_1} - 1\right) VI}{\phi}. \tag{302}$$

Placing

$$\left(\frac{1}{p_1} - 1\right) = j,$$

$$E'I = \frac{J + jVI}{\phi}. \tag{303}$$

Since

$$V = Ir + A,$$

$$E'I = \frac{J + jI^2r + jIA}{\phi} \tag{304}$$

and

$$I = \frac{\phi E' - jA}{2\,rj} - \sqrt{\left(\frac{\phi E' - jA}{2\,rj}\right)^2 - \frac{J}{rj}}, \tag{305}$$

which is the total current supplied by the battery to the rotary.

Only the negative sign is placed before the radical, as it gives the only practical values.

Case 3, rotary converter with direct-current booster driven by its own motor. In this case only the current to be transformed goes to the rotary from the battery. The current through the

booster is the sum of the currents for the rotary and the booster motor.

$$\text{Input to the rotary} = \frac{J}{\phi} \text{ watts.} \tag{306}$$

Voltage of direct current at rotary brushes

$$v' = E' + A + Fr = E + Fr, \tag{307}$$

in which F is the current from battery to converter for transformation to alternating current.

$$F = \frac{J}{\phi (E + Fr)} \tag{308}$$

and

$$F\phi (E + Fr) = J, \tag{309}$$

from which

$$F = \sqrt{\left(\frac{E}{2r}\right)^2 + \frac{J}{\phi r}} - \frac{E}{2r}. \tag{310}$$

$$\text{Booster energy output} = (A + Fr)(F + I_B), \tag{311}$$

I_B being the current supplied by the battery to drive the booster motor.

$$\text{Booster motor input} = \frac{(A + Fr)(F + I_B)}{p_1 \times p_2}. \tag{312}$$

Loss in booster and motor is

$$\frac{(A + Fr)(F + I_B)}{p_1 p_2} - (A + Fr)(F + I_B) \tag{313}$$

$$= \left(\frac{1}{p_1 p_2} - 1\right)(A + Fr)(F + I_B). \tag{314}$$

Placing $\left(\frac{1}{pp_1} - 1\right) = j'$ equation 314 becomes

$$j'(A + Fr)(F + I_B). \tag{315}$$

$$\text{Battery energy output} = E'(F + I_B). \tag{316}$$

$$E'(F + I_B) = \frac{J}{\phi} + j'(A + Fr)(F + I_B). \tag{317}$$

From which

$$I_B = \frac{\frac{J}{\phi} + j'F(A + Fr) - FE'}{E' - j'(A + Fr)}. \tag{318}$$

As an example to illustrate and compare the three cases discussed take

$J = 450$ K.W.

$\phi = 88$ per cent for 100% overload.

$E = 500$ volts.

$\epsilon = 2.1$ volts per cell.

$\epsilon' = 1.65$ volts per cell.

$N = \frac{500}{2.1} = 238$ cells.

$p_1 = 86$ per cent at 200% overload.

$p_2 = 86$ per cent at 200% overload.

$r = 0.05.$

$E' = 238 \times 1.65 = 393$ volts.

$A = E - E' = 107$ volts.

$j = \frac{1}{0.86} - 1 = 0.163.$

Then for case 1, on discharge, from equation 291.

$$\text{Booster current} = \frac{1.67 \times 450{,}000}{500 \times \sqrt{3}} = 867.7 \text{ amperes per phase.}$$

From equation 298,

$$\text{Booster voltage} = \frac{0.05 \times 450{,}000 + .88 \times 393 \times 107}{1.67 \times .88 \times 393 - 0.163 \times 0.05 \times 867.7 \times \sqrt{3}}$$
$$= 105.2 \text{ volts.}$$

Booster output $= 867.7 \times 105.2 \times \sqrt{3} = 158$ K.W.

Input to booster $= \frac{158}{.86} = 183.8$, say 184 K.W.

Loss in booster $= 184 - 158 = 26$ K.W.

Output of rotary $= 450 + 26 = 476$ K.W.

Input to rotary $= \frac{476}{.88} = 541$ K.W.

Battery current $= \frac{541{,}000}{393} = 1376.6$ amperes.

Electrical energy delivered by rotary as a generator $= 476 - 184 = 292$ K.W.

Energy delivered as a motor to drive booster $= 184$ K.W.

Case 2; direct-current booster on rotary converter shaft.

For maximum discharge and minimum battery voltage,

$$E' = \epsilon' N = 1.65 \times 238 = 393 \text{ volts}$$

$$j = \frac{1}{.86} - 1 = 0.163.$$

Then from equation (305) the battery current to the booster and rotary is

$$I = \frac{.88 \times 393 - 0.163 \times 107}{2 \times 0.05 \times 0.163}$$

$$- \sqrt{\left(\frac{.88 \times 393 - 0.163 \times 107}{0.1 \times 0.163}\right)^2 - \frac{450{,}000}{0.05 \times 0.163}} = 1420 \text{ amperes.}$$

Energy supplied by battery = 1420 × 393 = 558 K.W.
Booster volts = 1420 × 0.05 + 107 = 178 volts.
Booster output = 1420 × 178 = 252.8 K.W.

Energy delivered to booster $= \frac{252.8}{0.86} = 293.9$ K.W.

Loss in booster = 293.9 − 252.8 = 41.1 K.W.
Energy output of rotary = 450 + 41.1 = 491.1.

Energy input of rotary $= \frac{491.1}{0.88} = 558$ K.W.

Case 3; rotary working with a direct-current booster having its own motor.

From equation 310,

$$F = \sqrt{\left(\frac{500}{2 \times 0.05}\right)^2 + \frac{450{,}000}{.88 \times .86}} - \frac{500}{2 \times 0.05} = 936 \text{ amperes.}$$

$$\text{Input to rotary} = \frac{450{,}000}{.88} = 511{,}363 \text{ watts.}$$

To compute booster motor current, determine the several quantities in equation 318 separately.

$$\frac{J}{\phi} = 511{,}363 = \text{rotary input.}$$

$$j' = \left(\frac{1}{.86 \times .86} - 1\right) = 0.352.$$

Booster voltage is

$$(A + Fr) = (107 + 936 \times 0.05) = 153.8 \text{ volts.}$$

$$FE' = 936 \times 393 = 367{,}848 \text{ watts.}$$

Then

$$I_B = \frac{511{,}363 + (0.352 \times 936 \times 153.8) - 367{,}848}{393 - 0.352 \times 153.8} = 572.8 \text{ amperes.}$$

Total current supplied by battery = 936 + 572.8 = 1508.8 amperes.

Energy supplied by battery = 1508.8 × 393 = 592.9 K.W.
Booster output = 1508.8 × 153.8 = 232 K.W.
Booster and motor loss = 0.352 × 232 = 81,600 watts.

Total energy used by booster, motor and rotary is 511,363 + 81,600 = 592.9 K.W., checking with energy output of battery.

Size of motor for this maximum output is $\frac{232}{0.86} = 270$ K.W.

Comparing the three systems the following are the results.

Battery output for first case	1375	amperes.
" " " second case	1420	"
" " " third case	1509	"

Sizes of boosters, 200 % overload basis:

First case	52.8 K.W.
Second case	83.2 K.W.
Third case	77.1 K.W.

Sizes of converters, 100 % overload basis:

First case	237.8 K.W.
Second case	245.5 K.W.
Third case	225 K.W.
Third plus motor = 90 + 225 =	315 K.W.

The first case therefore is the most efficient and least costly of the three.

*Split-Pole Rotary Converter.**

This is a special form of converter in which the voltage ratio between the alternating and direct current sides may be widely varied. When interposed between an alternating-current circuit and a storage battery, the circuit will send current into the battery if the voltage ratio be so adjusted that the direct-current voltage is higher than that of the battery for a normal impressed alternating-current voltage at the slip rings. If, however, the adjustment be such that the direct-current voltage is lower than that of the battery when the normal line voltage is impressed at the slip rings, the battery will discharge through the converter and supply energy to the alternating-current line.

This machine differs from the ordinary standard converter in that it has subdivided field poles, all portions of the poles being excited from a constant-potential source of current, while a variable and reversible source also excites all portions, but certain parts of each pole have their windings, which are excited by the variable and reversible source, connected in opposition relatively to the other portions of the same pole. Fig. 288 illustrates this arrangement. a, b and c are the sections of one pole, each section carrying

* Am. Pat. Nos. 679812, 679813 to J. E. Woodbridge.

the windings 1, 2, 3, which are all wound in the same direction, are connected in series, and receive current through the mains L_1, L_2, which comes from a constant-potential source. These windings, then, magnetize each of the sections in the same direction and make all the sections of the same polarity.

Windings 4, 5 and 6 are likewise all connected in series, but the winding 5 on pole division b is reversed in direction relatively to

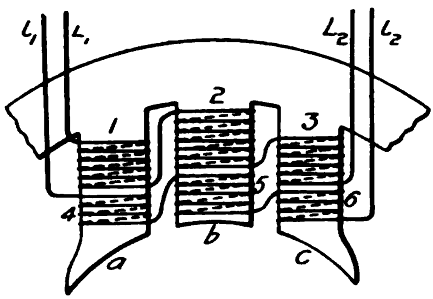


FIG. 288 Connections of Pole Divisions on Split-pole Converter.

the windings 4 and 6 on divisions a and c. Therefore if a current flow takes place through this second set of windings, in a direction to strengthen divisions a and c division b will be weakened, and if the current is in a direction to strengthen b, c and d will be weakened. Therefore, except when the current through windings 4, 5 and 6 is zero, the middle division is stronger or weaker than the other two, so that in addition to the magnetic lines from one complete pole of one general polarity to the next adjacent complete poles of the opposite general polarity, there will also be a local flow of magnetic lines between the middle section of each pole and the two outside sections, which local magnetization passes through the converter armature and may be in either direction, to or from the middle pole according to the direction of current through the windings 4, 5 and 6. These windings are connected to mains l_1, l_2, which receive current from some form of alternating-current regulator, the Woodbridge regulator described in Chapter XLVII being used in connection with this machine. The current flow through windings 4, 5 and 6 is therefore automatically varied in degree and direction with changes in load on the alternating-current circuit to which the converter is connected.

Referring to Fig. 289, the line AB represents the developed armature periphery, the direct-current brushes being located at A and D. The lines a, b and c represent the field strength of the three sections of one pole, and the lines d, e and f that of the other pole under normal conditions of excitation. The result of this excitation will be a certain ratio between alternating and direct current voltage. If the excitation of the outer pole sections a, c, d and f be increased, and that of the middle sections b and e be decreased, the field distribution may then be represented as the resultant of the auxiliary field g, h, i, j, k and l superposed upon

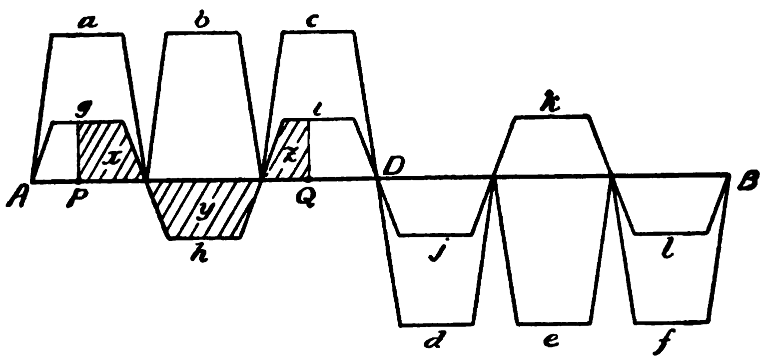


FIG. 289. Flux Distribution in Split-pole Converter.

the normal field. Considering the electromotive force developed in a section of the armature between the points P and Q, which may be taken to represent two of the three phase taps located 120° apart, it will be seen that the auxiliary field will have absolutely no effect on the voltage in this section at any point in the revolution, for the sum of the shaded areas x and z is always equal and opposite to the shaded area y. The auxiliary field therefore interposes into the armature section between the points P and Q equal and opposite amounts of field flux, which exactly neutralize each other in the generation of electromotive force between P and Q. The effect, however, of the auxiliary field on the direct-current voltage between the points of brush contact A and D is to produce an increase in that voltage, for the reason that between these two points there are two areas of positive flux and only one area of negative flux due to the auxiliary field. Theoretically, therefore, this auxiliary field would produce an increase or

decrease in the direct-current voltage without any effect whatever on the magnitude or wave shape of the alternating voltage between the points P and Q, provided these points are spaced 120° apart.

Practically, however, it is necessary to allow a neutral area of

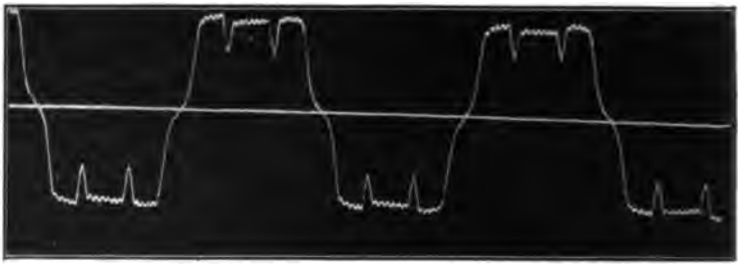


FIG. 290. Flux Distribution in Split-pole Converter, Equal Excitation of all Sections.

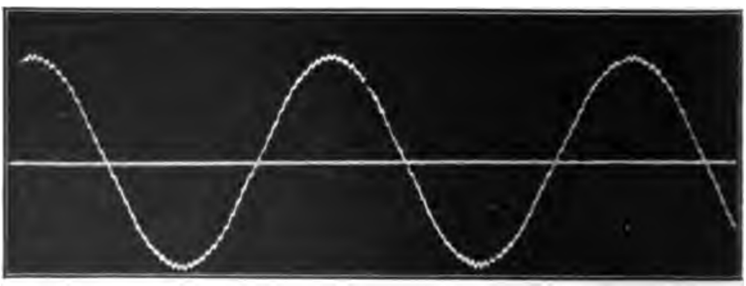


FIG. 291. Curve of Electromotive Force, Split-pole Converter.

zero field strength at the points A and D for commutation. This modification produces some disturbance of the wave shape of the alternating counter electromotive force, which, however, is not sufficient to interfere with the practical operation of the machine. In Figs. 290 to 295 inclusive are shown oscillograph records giving the distribution of field flux obtained by an exploring coil and the corresponding wave shape of alternating electromotive force across two of the three phase collector rings, taken from a 500-kw. split-pole converter of this type. Fig. 290 shows the normal field distribution with all three sections of the pole equally excited and Fig. 291 is the corresponding wave shape of electromotive force;

direct-current voltage 250. Fig. 292 shows the field distribution with the outer sections increased and the middle section reduced in excitation, while Fig. 293 shows the corresponding wave shape of electromotive force; direct-current voltage 280. Fig. 294 shows

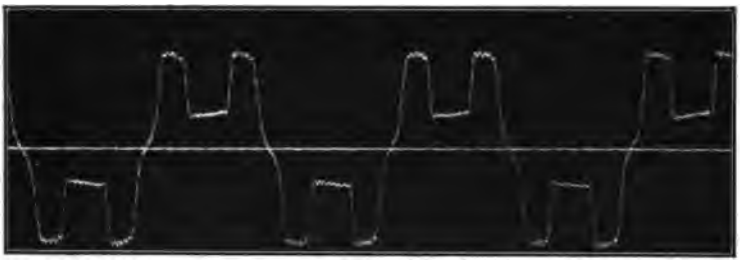


FIG. 292. Flux Distribution in Split-pole Converter, Diminished Excitation of Middle Section.

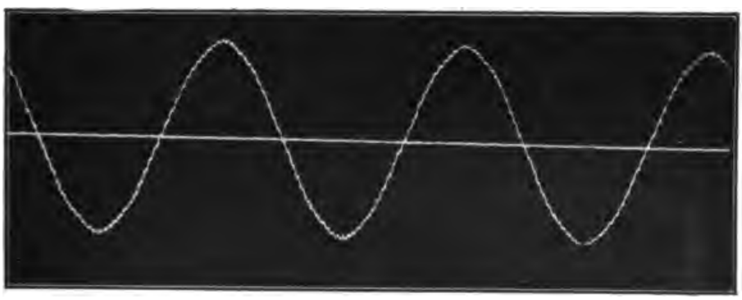


FIG. 293. Curve of Electromotive Force, Split-pole Converter.

the field distribution with the outer sections weakened and Fig. 295 shows the corresponding wave shape of electromotive force; direct-current voltage 232. It will be noted that the difference in the wave shapes for these three different conditions of field excitation is scarcely perceptible. The alternating electromotive force was held constant throughout.

In a later development of the split-pole converter suggested by Mr. J. L. Burnham, only two pole sections are employed. One of these has a pole arc covering a considerable portion of the total pole pitch, and constitutes the principal pole, while the other covers a smaller arc and is used as an auxiliary or regulating pole. A

simple explanation of the theory of this machine may be had by reference to Figs. 296 and 297. In Fig. 296 the line OP represents the alternating voltage developed by the principal pole section. The line OF may be taken to represent in amount and phase position the electromotive force developed by the auxiliary pole, these



FIG. 294. Flux Distribution in Split-pole Converter, Diminished Excitation of Outer Sections.

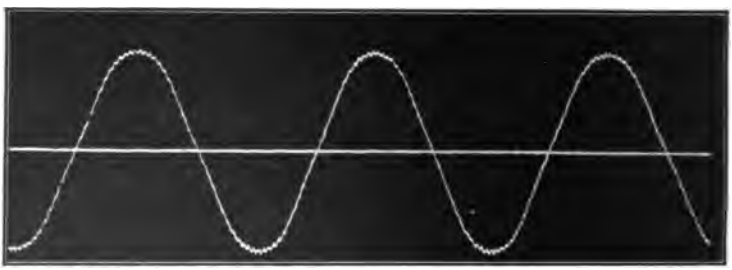


FIG. 295. Curve of Electromotive Force; Split-pole Converter.

two electromotive forces being displaced by the angle p, which represents the angle between the axes of the two fields. The line OR will then represent the resultant alternating electromotive force. If the excitation of the auxiliary field is zero, the line OP will represent the alternating electromotive force. It will be noted that the line OR is but very little longer than the line OP. The direct-current electromotive force will be represented by the algebraic sum of OP and OF. With zero excitation of the auxiliary pole this direct-current electromotive force will be represented by OP, while with an excitation corresponding with the line OF the

direct-current electromotive force will be represented by OD. If the main field excitation is reduced to OP′ when the auxiliary field has an excitation corresponding with OF, the resultant alternating electromotive force will be represented by OR′, equal to OP, while the direct-current electromotive force will be represented by OD′. It will thus be seen that the direct-current electromotive force has been increased from OP to OD′ without any change in the magnitude of the alternating-current electromotive force. If the auxiliary pole be given an initial negative excitation corresponding with the line OF_0, such that the resultant OR_0 is at right angles to OF_0, then any variation of excitation of the auxiliary pole on either side of this point will produce a minimum change in the

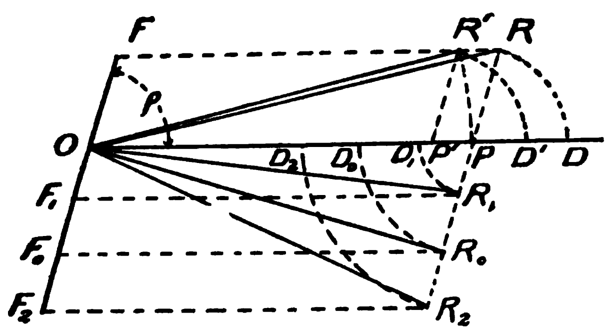


FIG. 296. Diagram of Currents and Electromotive Forces in Split-pole Converter.

alternating electromotive force, provided the main field excitation is maintained constant, or will require the least variation in the excitation of the main field to maintain constant alternating electromotive force. Thus if the negative excitation of the auxiliary field be decreased to F_1, the resultant alternating electromotive force will be represented by OR_1, while if the negative excitation of the auxiliary pole be increased to F_2, the alternating electromotive force will be represented by OR_2. The corresponding direct-current electromotive forces will be represented by OD_0, OD_1, and OD_2, respectively. For hand control it is of course permissible to vary the excitation of both the main and auxiliary fields, in order to vary the direct-current voltage without disturbing the power factor. With automatic control it is, however, desirable to limit the control to a single field coil; and to accomplish this with minimum disturbance to the power factor it is necessary to work

on either side of the point F_0, which represents the mean excitation of the auxiliary pole. In Fig. 297 are illustrated the results obtained by designing the machine with a pitch of 90° between the main and auxiliary pole sections. In this case the mean excitation of the auxiliary pole for minimum change in the alternating-current electromotive force is zero, the excitation of this section being varied on either side of zero to produce a change of direct-current electromotive force above and below the mean. It can be readily shown that if the lines OF_1 and OF_2 are each equal to 20 per cent of the line OP, corresponding with a variation in direct-current electromotive force of 20 per cent above and 20 per cent below the mean, the lines OR_1 and OR_2 will be about 2 per cent greater than the line OP, resulting in a total variation of 1 per cent in the alternating electromotive force on either side of the normal.

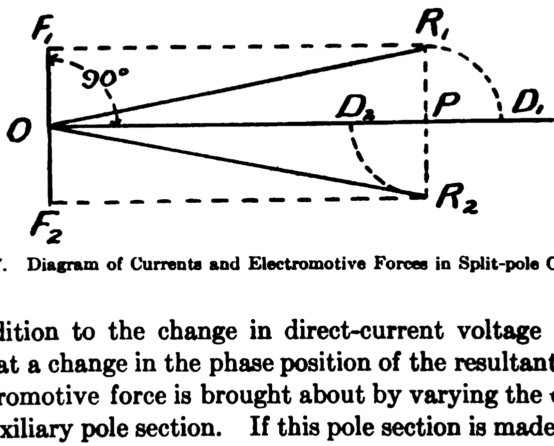


FIG. 297. Diagram of Currents and Electromotive Forces in Split-pole Converter.

In addition to the change in direct-current voltage it will be noted that a change in the phase position of the resultant alternating electromotive force is brought about by varying the excitation of the auxiliary pole section. If this pole section is made the trailing section, this shifting of the phase position will coöperate with the change in direct-current voltage in bringing about a quick transfer of energy between the battery and the alternating-current circuit, by advancing the phase of the alternating-current voltage, thus causing the converter to deliver energy to the alternating-current circuit at the same time that the direct-current voltage is reduced and energy is thus taken from the battery.

The voltage ratio variation required in these converters must be such that with the alternating-current voltage substantially constant, the minimum direct-current voltage is N × 1.65, while the maximum direct-current voltage is N × 2.6, for the converter is

the only machine available for charging the battery. Taking normal open-circuit voltage per cell as 2.1 volts, the minimum direct-current voltage is 0.45 N below the normal voltage, while the maximum is 0.5 N above it. This is practically a variation of 25 per cent in either direction, which change must be produced by the maximum current flow from the regulator to the regulating field coils. This change in voltage ratio may be reduced by providing taps on the transformers connected to the converter so that a manual adjustment of the voltage can be made in a few steps, the automatic controller regulating between the limits fixed by the steps.

The determination of battery current for a given output to or input from the alternating-current line is very simple, as there is only one machine to be considered.

If J = watts to be delivered to line,

$$\frac{J}{\phi} = \text{watts to be delivered by battery}$$

and

$$I = \frac{J}{E'\phi} = \text{current to be delivered by battery.}$$

Thus for J = 450 kilowatts, ϕ = 88 per cent, and a minimum battery voltage = 393 volts.

$$I = \frac{450{,}000}{393 \times .88} = 1301 \text{ amperes.}$$

This current is less for the same conditions than that required for any of the other systems of alternating-current regulation that have been considered.

An interesting example of an alternating-current plant regulated by a storage battery and split-pole converter is that in the works of the U. S. Steel Corporation at Gary, Illinois.

The regulator employed is the rotating mechanism devised by Woodbridge and described in Chapter XLVII.

Fig. 298 is a simplified diagram of the connections. A, A are the armatures of the 3-phase, alternating-current generators feeding to the bus bars 1, 2, 3; t, t, t are series transformers in the generator lines, the secondaries of the two sets being connected to the small bus bars 4, 5, 6, which latter, therefore, carry currents proportional to the total output of the generators; T, T, T are transformers having adjustable secondaries, their primaries receiving the total current from 4, 5, 6.

E is the exciter for the field regulation of the rotary converter. Its armature H is provided with six collector rings connected to its winding at equidistant points. These collector rings are connected to three current transformers in the alternating-current circuit

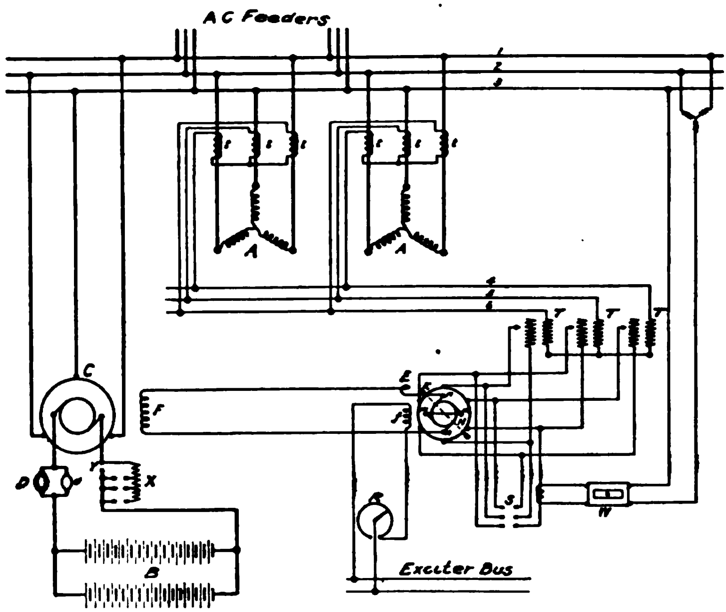


FIG. 298. Diagram of Connections for Alternating-current Regulation at Gary, Ill.

whose load is to be regulated. The alternating currents thus transmitted through the armature winding will set up a revolving field proportional to these currents. A synchronous motor (not shown) connected to the alternating-current circuit revolves the armature in a direction opposite to that of the field rotation, thus holding this field stationary in space. The machines are so designed that at unity power factor this field will take the direction indicated by the arrow K. To the armature winding is connected a commutator upon which bear two pairs of brushes. One pair of brushes, m, m, called the auxiliary brushes, is located at points of maximum potential difference due to the field K. The other pair of brushes, n, n, is connected to the regulating field coils F of the split-pole converter c.

The fields of the exciter are provided with two windings.

One of these is a shunt winding energized from the exciter bus bars and controlled by the rhesotat R. The current in this field winding may be adjusted to neutralize the field K set up by the alternating current at some particular load on the alternating-current circuit. Under these conditions there will be no potential across the brushes m, m, and they may be short-circuited, as shown in the diagram. This being done, any change in the alternating-current load above or below the value for which the shunt field of the exciter has been adjusted will produce a difference of potential between the brushes m, m. A small change in the alternating-current load will be sufficient to cause a very considerable flow of current through the short-circuit connection between these brushes, and this flow of current will set up a second field at right angles to the field K and of considerable magnitude. This second field produces a potential across the brushes n, n, and a corresponding flow of current in the regulating field F. If the alternating-current load has increased, the direction of flow of current in the field coil F will be such as to cause the battery to discharge, while if the alternating-current load has decreased, the current in F will be in the opposite direction, causing the battery to charge.

The second field winding on the exciter is connected in series with the field coil F and serves to neutralize the armature reaction due to the current output from the brushes n, n, and thus makes the machine more sensitive. If the power factor is not unity, the alternating current transmitted from the current transformers through the armature winding may be divided into two components; one of these, the energy component, will produce the field K, while the other being at right angles to this, will pass directly through the short circuit between the brushes m, m and have no appreciable effect on the regulation. It will be seen, therefore, that this machine is responsive to the energy component of the alternating current.

In the Gary installation this exciter is an eight-pole machine, the armature being provided with a four-pole winding, and is driven by a four-pole synchronous motor. There are eight brushes bearing upon the commutator, four of these being the auxiliary brushes, which are short-circuited, while the other four are connected in pairs and constitute the main terminals of the machine.

One special feature of the regulating apparatus in this installation is the short-circuiting switch, across the secondaries of the totaliz-

ing current transformers. When this switch is closed all the current transformers are short-circuited through the totalizing current transformers, and at the same time the exciter is short-circuited on the alternating-current side. This reduces the exciter voltage to zero and regulation ceases, but owing to the high armature reaction of the exciter only a small flow of current is set up through the short-circuit switch. In fact, at times when the total load on the plant is just equal to the average load which is being maintained on the generators, so that the battery is neither charging nor discharging, the exciter voltage will be zero under normal operating conditions. The short-circuit switch may therefore be closed without producing any effect whatever. Any variation of load from this point will produce a flow of current through the short-circuit switch proportional to the increase or decrease of load, but will not affect the voltage of the exciter. In one of the leads to this short-circuit switch is connected the current coil of a wattmeter, W, its voltage coil being suitably connected to indicate the energy component of the current passing through the short-circuiting switch. This wattmeter provides a means for adjusting the shunt field of the exciter to any predetermined average load on the generators before opening the short-circuiting switch. In this way the process of putting the regulating apparatus into service is much simplified.

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